THE DEVELOPMENT OF NEW TECHNIQUES FOR THE MANUFACTURE AND TESTING OF CYLINDRICAL SHELLS

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Thomas Alexander Haack

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THE DEVELOPMENT OF NEW TECHNIQUES FOR THE MANUFACTURE

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Approved:

Wilfred H. Horton, Chairman

Stanley C. Bailey

James I. Craig

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SUMMARY

The work reported in this thesis demonstrates that the technology necessary for the construction of versatile stiffened plexiglass model shells with or without reinforced cutaways has been developed. Such models are of great value in studies of shell instability.

In the majority of large shell tests the degree of flatness at the vehicle extremities has been a question of concern. Methods of machining the ends of such specimens which are capable of ultra-precision have herein been devised and their impact demonstrated. General processes for modifications of value in parametric studies have also been devised.

CHAPTER I

INTRODUCTION

Ring and stringer stiffened shells are one of the most common aerospace structural forms. Even so, it is an accepted fact among theoreticians, experimentalists, and practical engineers that the design of stiffened shell bodies under axial compression is marred by uncertainty. There is no universally accepted theoretical design procedure, and there exists a paucity of experimental data from which to formulate empirical rules. Table 1 (1) lists the currently available test information. It may be readily seen from this summary that there is a pressing need for experimental work on large scale structures of this type. This need was well expressed by Professor Lee in the concluding remarks of his paper (2) presented at the NASA Symposium on Instability of Shell Structures, when he said:

> A great deal of mathematical difficulty is expected in any theoretical refinement (of shell theory including imperfection parameters). They may be alleviated, however, if the theoretical development is guided by refined experiments. Most of the experimental results available in the literature are usually presented in terms of only the critical buckling load and the final mode of buckling. New experimental results on the complete development of the buckling stress pattern, prebuckling and postbuckling, may provide a physical basis for a better theoretical insight into this difficult problem.

In order to help fill this clear need for further experimental data, the School of Aerospace Engineering at the Georgia Institute of Technology is actively engaged in a broad study on the stability of

Table 1. Summary of Stiffened Shell Test Program

Test Class	Principal Investigator	Date	Number of Tests	Test Description
RING STIFFENED				
	Peterson	1956	25	Moderate scale specimens Panel instability predominated
	Singer	1969	18	Small scale machined shells Panel and general instability
	Tenerelli and Horton	1969	9	Small scale machined shells Program included limited wall motion studies
	Singer, Arbocz, and Babcock	1970	13	Small scale machined shells Program included extensive mapping of initial imperfections and wall motion under axial load
CORRUGATED				
	Dickson	1966	5	Ring stiffened large scale cylinders
	Peterson	1966	5	Ring stiffened large scale cylinders Testing in bending
	Anderson	1966	2	Ring stiffened large scale cylinders Inside and outside rings evaluated

Table 1. Summary of Stiffened Shell Test Programs (Continued)

Test Class	Principal Investigator	Date	Number of Tests	Test Description
STRINGER STIFFENED				
	Peterson	1959	6	Large scale, riveted construction
	Peterson	1963	17	Forty-eight inch diameter, riveted construction
	Card	1966	12	Integral milled and riveted stiffeners Both inside and outside stiff- eners tested
	Weller, Singer and Nachmani	1970	86	Small scale machined specimens
	Singer, Arbocz, and Babcock	1970	3	Small scale machined specimens, part of larger program on ring stiffened shells
RING AND STRINGER STIFFENED				
	Card	1964	7	Large scale shells tested in bending Skin wrinkling preceded general instability
	Lockheed (Missiles & Space Co.)	1965	10	Data not available in open literature Photographs show general insta- bility on only one shell

Table 1. Summary of Stiffened Shell Test Programs (Continued)

Test Class	Principal Investigator	Date	Number of Tests	Test Description
NON-REPRESENTATIVE TESTS				
	Milligan	1965	51	Small scale machined shells Excessive skin thickness variation and closely spaced, low eccentricity stiffeners
	Lakshmikantham	1965	6	Similar specimens to the above
	Katz	1965	21	Skin wrinkling preceded general instability Low deflectional stiffness of reinforcement did not provide nodes in this pattern
EARLY TESTS				
	Hoff	1944	13	Riveted shells not representative of contemporary construction
	Dunn	1947	174	Riveted shells not representative of contemporary construction Results of these tests formed the basis for the "Shanley Criterion"

shell structures under various loadings. The current research deals most directly with the behaviour of stiffened shells under axial compression. The program can best be outlined in terms of two phases of model and full scale testing which are designed to complement each other in the achievement of far reaching goals which include:

(1) The development of non-destructive methods of shell testing.

(2) Determination of the effects of parameter changes on a given specimen.

The value of the first goal is obvious. Rather than mere determination of the critical load by subjecting a shell to increasing loads until failure, this approach provides data from an unscathed specimen which can then be used in further tests, either in the same form or in a modified condition. The advantages of using the same shell rather than a number of shells for a series of tests are emphasized by the following facts:

(1) No two specimens can ever be exactly alike--the effects of variations between specimens can effectively mask items of interest in the test data obtained.

(2) Large shells are very expensive--it is economically unfeasible to construct the number of shells needed for meaningful parametric studies.

Attainment of the first stated goal clearly makes the second possible. That is, once methods for the non-destructive determination of shell characteristics under load have been developed, parametric studies may be undertaken on a progressively modified basic vehicle. Thus it may confidently be anticipated that the changes in behavioral pattern are due solely to the alterations made to the parameter of interest.

The specimens being tested in one phase are very large, stringer and ring stiffened, circular cylindrical shells of aluminum. Their construction involves a very high standard of manufacturing quality and extensive use is made of modern techniques such as metal-to-metal bonding. Because of their excellent quality and large size, these specimens are expensive. Hence the total number of shells available is restricted.

Therefore, this phase of the program is supported by another, employing small shells constructed of plexiglass. These models are relatively easy and economical to construct to a good degree of quality. It is in this model testing phase that new ideas and concepts are first tried out. The ones which prove successful are then applied to the large shell tests to determine their applicability to the full scale situation.

The model test program has been used to establish accurate methods for the prediction of critical load from observations made in the subcritical regime. Work to date (1, 3, 4, and 5) has shown conclusively that these plastic model shells have great value in such studies.

The plastic shells are also being used to examine the effects of parameter changes. Parameters of particular interest are shell length, stringer and ring cross sectional properties, and the presence of various types of holes and discontinuities in the shell wall. The plexiglass models are relatively easy to modify, and therefore a single basic shell can be tested in various stages of modification. Consequently, deficiencies in loading and general imperfections of form remain a consistent factor from test to test. Using this process, Ford (1) performed a parametric study of the influence of ring stiffness on stringer stiffened shells. Singhal (4) is extending this work considerably using a much wider variety of stiffening arrangements.

It is not necessary for the small shells to be exact scale models in order for them to be effective in the development of techniques applicable to the large shell program. However, their structural elements must display both appropriate stiffness in bending and torsion and realistic ratios of stiffness in relation to one another. These stiffness requirements and the need for greater ability to modify a specimen under test begin to tax previous manufacturing techniques beyond their capability. There is a necessity to improve manufacturing technology for the plastic models. One of the purposes of this thesis is to satisfy this demand.

The need for parameter modification techniques extends to the large shell program. The required technology is of necessity different from that applicable to the plastic models because of the difference in shell construction, material, and size. Development of modification techniques directly applicable to the large shells is the second purpose of this thesis.

The present work contributes to both phases of the overall program and accordingly it is presented in two parts.

CHAPTER II

PLASTIC MODEL SHELLS

Typical construction techniques for the plastic models are discussed thoroughly in Ford's work (1). During this early work with plastic shells a very successful technique for the hot shrinking of solid square section rings was developed. Rings of this type are still employed as end reinforcements in present shell construction. These rings are formed by placing the proper length of square plastic bar stock into a circularly grooved fixture and heating to 300°F. The consequent natural shrinkage of the plastic when heated results in the ring being formed onto the inner surface of the fixture groove. Air quenching of the ring in the fixture speeds the cooling process and ensures that the ring will maintain its circular shape.

There is a disadvantage to rings formed in this manner, however, when used as other than end reinforcements. The smallest commercially available plexiglass bar stock is $\frac{1}{4}$" x $\frac{1}{4}$" and rings of this size exhibit far greater stiffness than desired in comparison with the shell wall material. It was found possible to reduce the section size by machining prior to forming the ring. However, it was still necessary that the resulting smaller section be square, rectangular, or otherwise doubly symmetric, since attempts at forming other shapes invariably resulted in rolling and warping of the ring upon heating.

Square or rectangular ring sections do not display realistic ratios of bending and torsional stiffness. Therefore, it became imperative that a method of forming rings with reduced stiffness characteristics be developed. In response to this requirement, a fixture was devised for the forming of "tee" section rings. Straight lengths of tee section were first machined from square stock. These were then formed in the new fixture using the heating process previously described. The new fixture was designed to prevent the rolling and warping previously encountered (Figure 1). Lateral restraint was applied to the upstanding leg of the tee but freedom of movement was allowed the whole ring in the radial direction. Tee section rings of very good quality were formed in this fashion (Figure 2).

Experience showed that the top surface of the tee upper flange should not be a machined surface. Rings on which this surface was machined displayed cracks along the top of the upper flange after heating while tees on which this surface was in an "as extruded" state displayed no such cracks.

It should be emphasized that the process described is not one of true hot forming since the plastic is not heated enough to flow or become soft. Forming at the 300° temperature allowed the use of easily manufactured wooden fixtures. The unnecessary use of temperatures higher than 300°F was found to result in a blemished or deformed ring surface due to excessive softness of the plastic while in contact with the relatively rough fixture. Rings formed at the 300°F temperature underwent no change in surface texture.

The principle of providing a fixture specifically designed to prevent section warpage during forming may be applied to a variety of

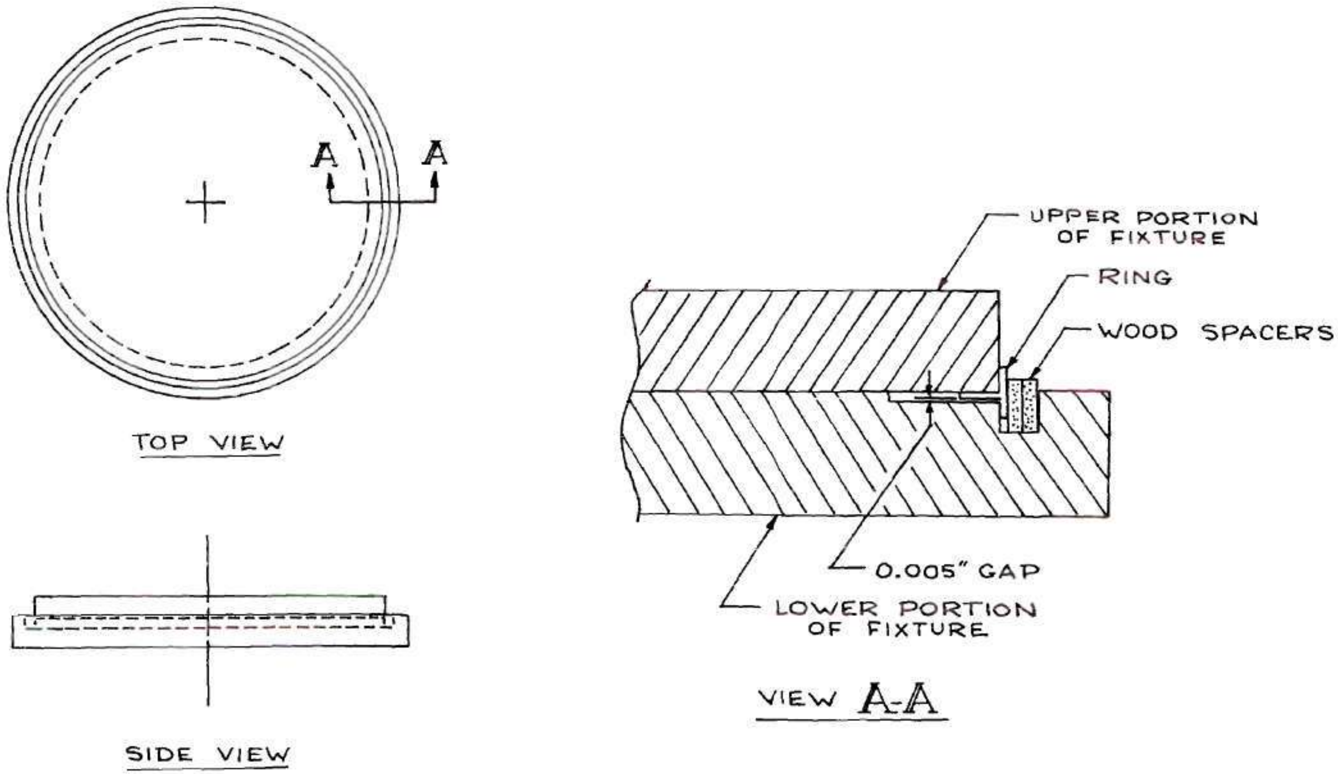


Figure 1. Fixture for Heat Shrinking of "T" Section Rings

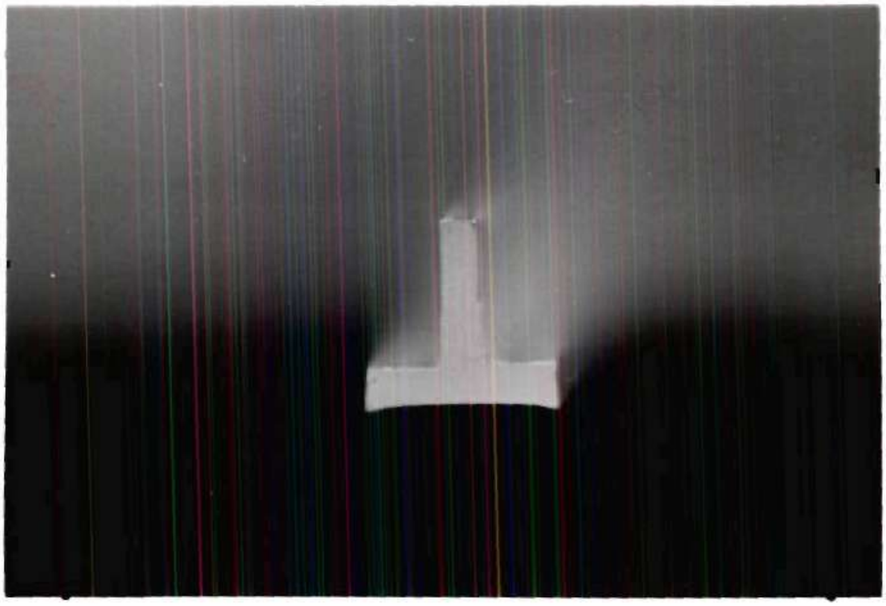


Figure 2. Section of Typical Formed Ring

ring sections which exhibit realistic ratios of flexural and torsional stiffness. This extends the usefulness of the plastic models considerably. This technique, however, is still subject to a limitation which it shares with previous stringer manufacturing processes. As mentioned earlier, it is necessary to machine a straight length of the section desired before forming it into a circular ring. The same machining process has been used to produce "tee" and "u" section stringers. The sections are machined on a horizontal milling machine using a fluid coolant to prevent surface and section distortion. This is a very time-consuming process. In addition, the difficulty and expense of the operation increase drastically as the desired section size and thickness decrease. With the facilities available, a practical limit to section thinness was found to be approximately 0.040". Stiffeners of still smaller thickness, and hence stiffness, were desired.

Along with the need for smaller stiffener sections, there existed a need for a process which would allow the ready manufacture of reinforcements to be applied around a variety of cutouts and other discontinuities planned in the skins of future models. Therefore, the use of true hot forming as a manufacturing technique to be used with the plexiglass was investigated in the present study.

Since not very much was known about hot forming of the plastic material, it was decided to try the concept by the forming of straight stringers from flat 0.030" sheet. In essence this task embodies all the principles which are required in a more complex situation, but the straight-forward geometry considerably simplifies the problems of tool construction.

To gain practical experience, several trial molds were machined from aluminum. These were designed to form a "hat" section stringer and consisted of a grooved female portion and a matching male portion incorporating a raised ridge (Figure 3). It was at first felt that the plastic might show a tendency to neck down excessively or tear as it was pulled across the upper corners of the groove in the female die by the descending ridge of the male portion. Hence, both these corners and the bottom of the ridge on the male portion were provided with generous radii (1/16"). This was later found to be unnecessary. In fact, the plastic was found to form so readily that merely "breaking" the sharp edges should suffice in future molds (Figure 4).

An initial preheat of the molds at an oven setting of 400°F for approximately 30 minutes was found necessary at the start of a production "run". Upon insertion in the hot mold, the plastic could be formed after 10 minutes heating at the same temperature. Under these conditions, the plastic became very soft and took on the shape and surface contours of the mold. Hence, a smooth mold was necessary. After removal of the mold from the oven, three to four minutes of cooling the formed section and mold inner surface with compressed air was found to be necessary prior to removal of the section from the mold. When this procedure was followed, the formed sections showed no tendency to "spring back" or otherwise deform from their shape. No tendency of the plastic to stick to the mold was encountered.

At first an attempt was made to load the mold with strips of the plastic pre-cut to the exact width required to form a stringer. Difficulty was experienced in aligning this long, narrow strip accurately

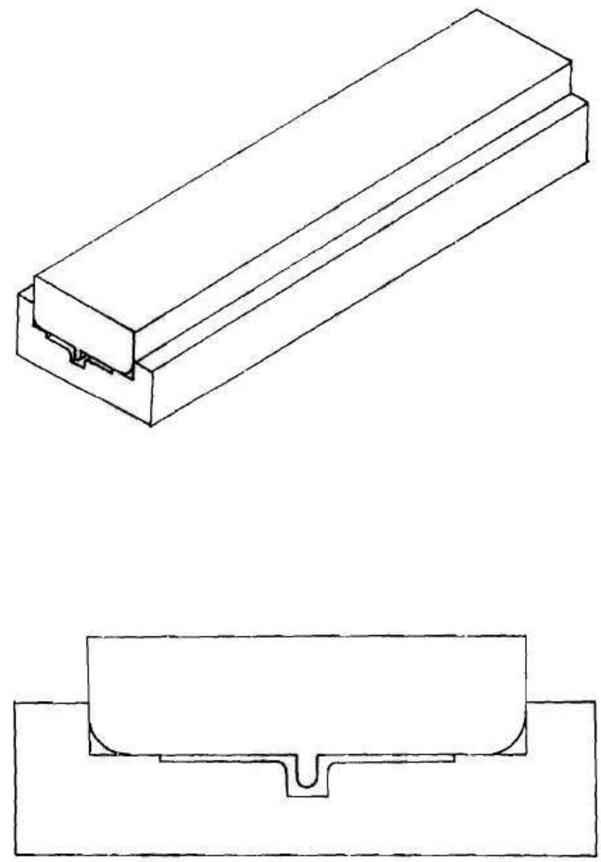


Figure 3. Trial Mold for the Hot Forming of Stringers

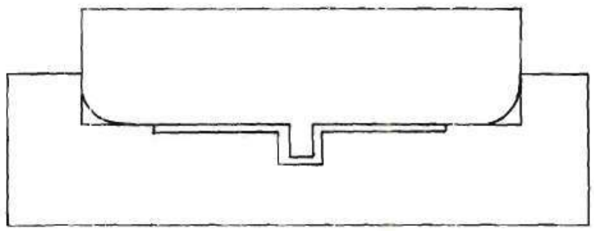


Figure 4. Proposed Mold Section

with the mold, as the plastic would immediately begin to deform in the lateral direction upon contacting the hot mold. Starting with a cold mold was considered impractical due to the excessive time involved in mold heat-up. The problem was overcome by using a wider strip of material. Sharp ridges machined on the male portion of the mold (Figure 5) scored the plastic along the desired stringer boundary, producing an accurate edge. Thus the excess material could be removed by "cracking" after the section was formed. With practice, complete cycle time of the hot molding process was reduced to 15 minutes. This included (1) plastic insertion, (2) heating, (3) forming, (4) air cooling, and (5) stringer removal.

After experience was gained with the trial molds, a production press was produced (Figure 6). Since cycle time for the process was independent of the number of stringers being produced at once, it was a distinct advantage to produce more than one stringer per cycle. Hence, the press was made capable of producing three 30" stringers at once. This press also incorporated knife-like ridges on the male portion to score the plastic during the forming process and facilitate subsequent separation of the three stringers. A typical resultant stringer is shown in Figure 7. With this mold, it was found possible to produce 30" stringers at the rate of 10 minutes per stringer or 15" stringers at 5 minutes per stringer.

The work described in the preceding paragraphs clearly shows hot forming to be a viable manufacturing technique for acrylic plastic model components. The process is by no means limited to production of straight stringers but is readily applicable to the forming

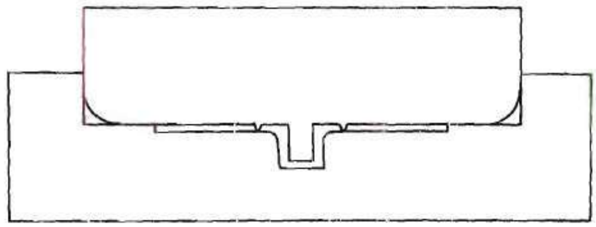


Figure 5. Stringer Mold With Cutting Ridges

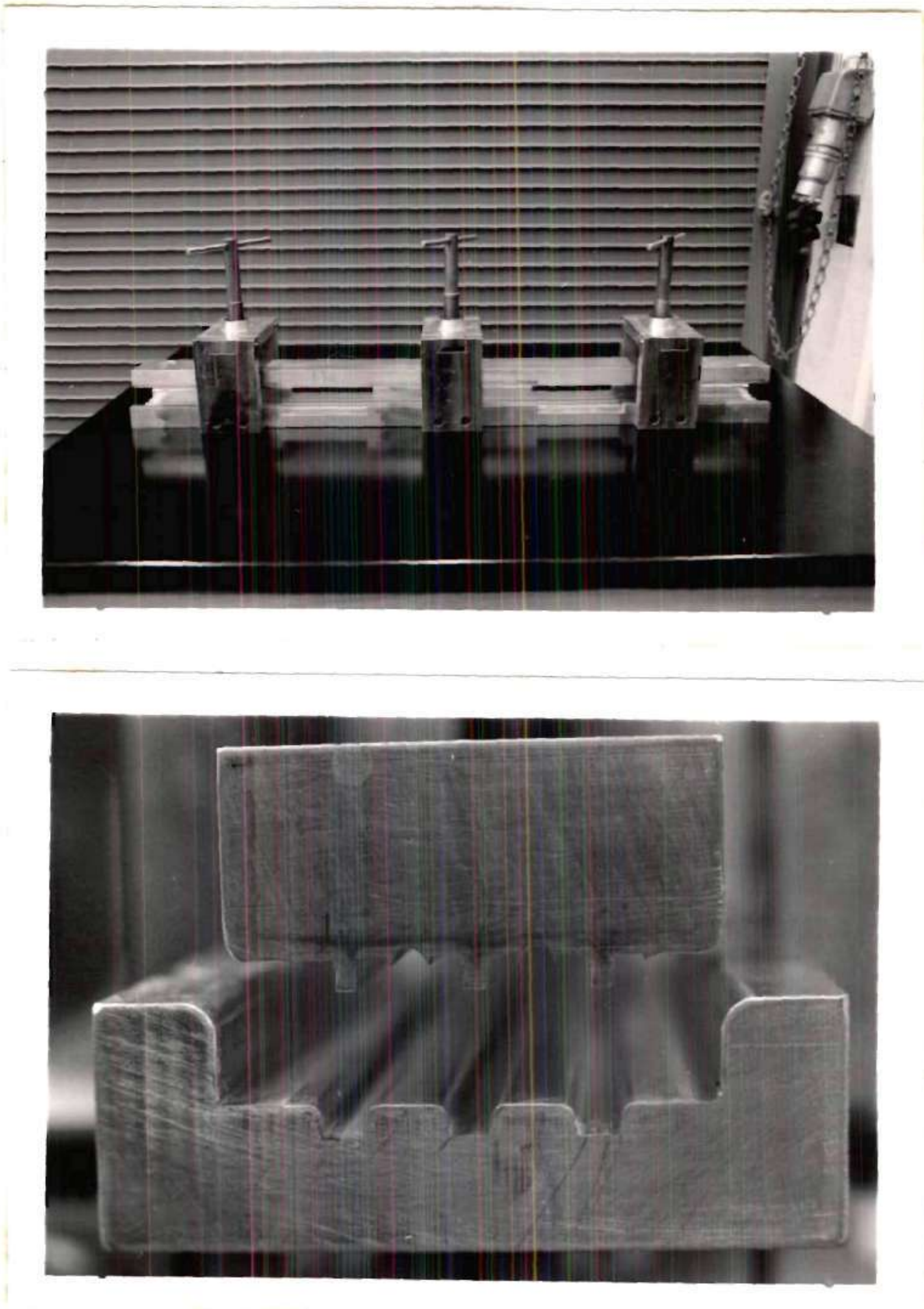


Figure 6. Production Press for the Hot Forming of Stringers

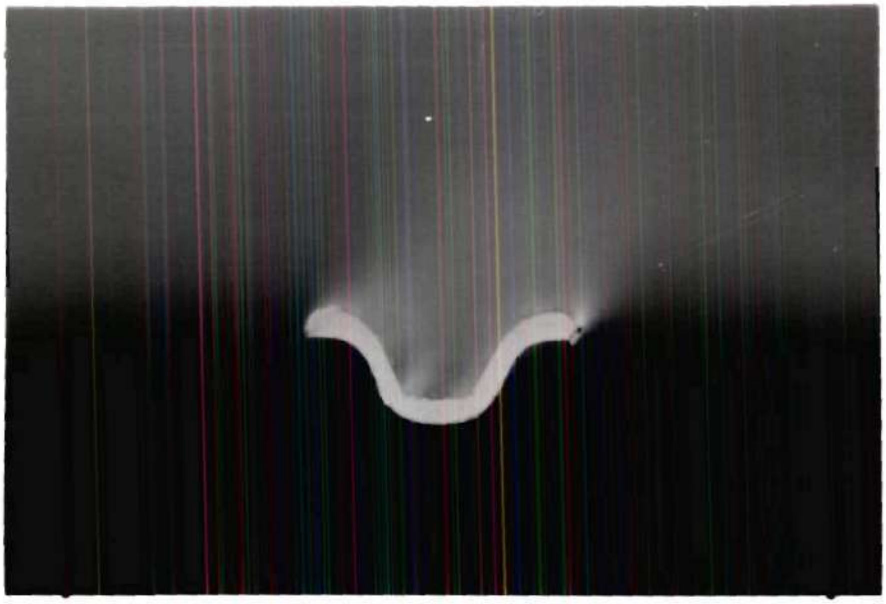
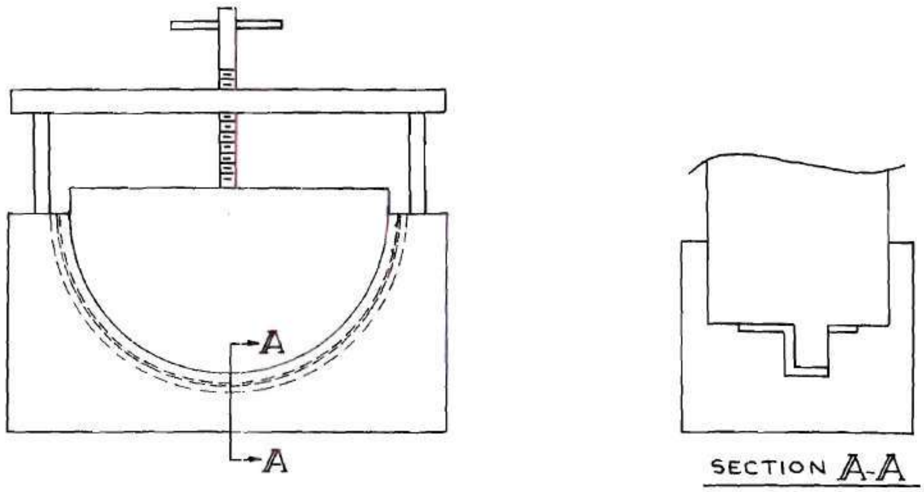


Figure 7. Section of Typical Formed Stringer

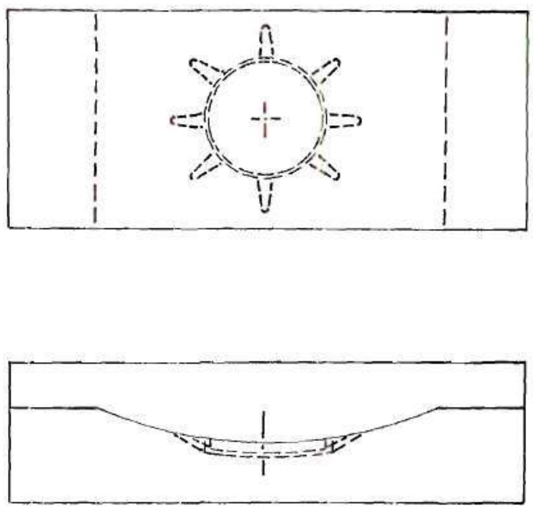
of rings and hole reinforcements. Figure 8 shows molds which might be used to hot form "Z" sections or "L" section rings and "Z" or "L" section fluted doublers for use around cutouts. The process is clearly applicable to a great variety of plastic structural elements.

Three high-quality shell models were subsequently constructed using the stiffening elements described in this section. The first (Figure 9) has "T" section srringers and "T" section rings produced by the heat shrinking process. The second and third (Figure 10) incorporate the "hat" section stringers produced by the hot forming process. The later two are of particular interest since they incorporate two distinct stiffnesses using the same stringer section. On one, the stringers are mounted on the shell wall concave side up, combining low stiffener torsional stiffness with high flexural stiffness (Figure 11). On the other, the stringers are mounted on the skin so as to form a closed element producing high torsional stiffness in conjunction with high flexural stiffness (Figure 12).

The manufacturing refinements detailed in this section considerably extend the application of acrylic plastics to model shell construction. The ability to hot form both the sheet material and machined sections broadens the type and nature of the specimens which can be constructed. There is no doubt that without these techniques the specimens required for programs involving cutouts and cutout reinforcements could not be economically constructed.



PROPOSED PRESS FOR HOT FORMING "Z" OR "L" SECTION HALF-RINGS (RING SECTIONS TO BE SPLICED DURING SHELL ASSEMBLY)



PROPOSED PRESS FOR FORMING "Z" OR "L" SECTION FLUTED DOUBLERS FOR USE AROUND CIRCULAR CUTOUTS IN SHELL WALL

Figure 8. Proposed Hot Forming Presses

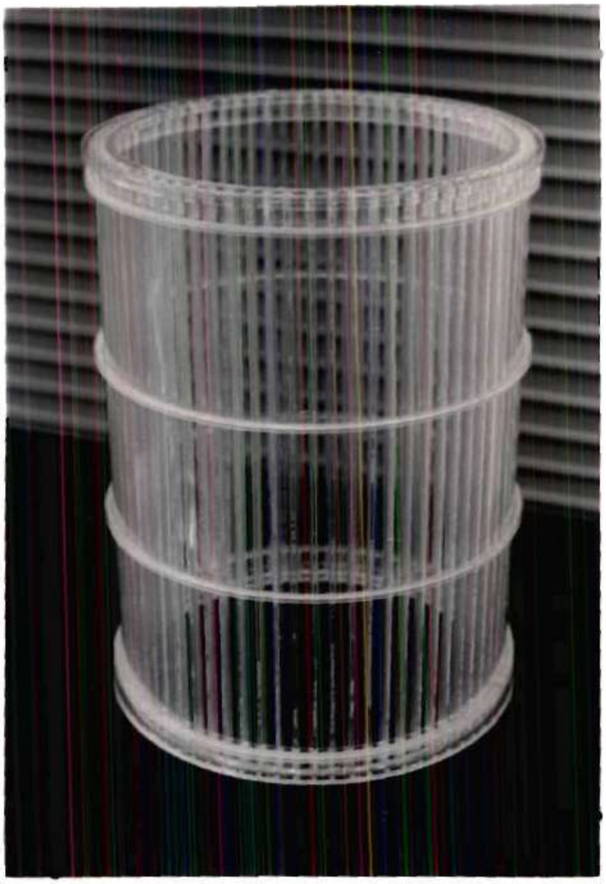


Figure 9. Specimen One With "T" Section Rings and Stringers

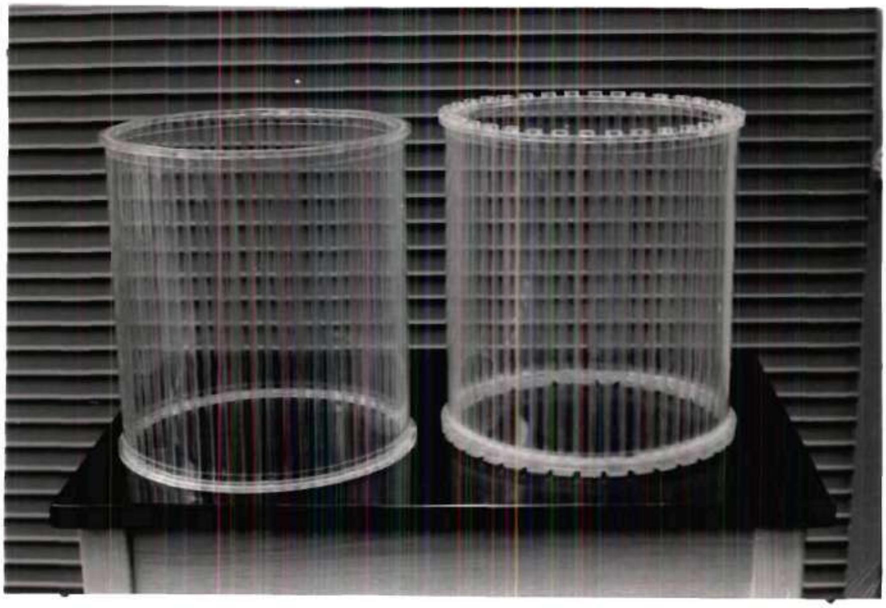


Figure 10. Specimens Two and Three With Hat Section Stringers

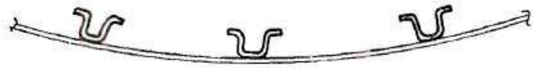


Figure 11. Stringer Mounting on Specimen Two

Figure 12. Stringer Mounting on Specimen Three

CHAPTER III

LARGE SHELLS

The test vehicles for the large shell program are constructed of aluminum. They are stiffened by "Z" section stringers hot bonded to the skin and by riveted "Z" section rings. A very high standard of quality was both demanded and obtained in their construction. Because of their high quality and large size, these shells are very expensive and the total number of specimens is limited. Five shells have been constructed to date. Their physical details are given in Table 2.

The large shell program has been carefully designed to extract the maximum amount of data from the specimens available. A typical series of modifications planned for a particular shell is shown in Table 3. To assure successful completion of both the basic shell test and the parameter modification schedule, it was necessary to both refine specimen loading technique and develop the technology required for shell modification. These requirements and developments are the subjects of this part of the thesis.

Basic Shell Tests

A major problem which has long plagued those involved in the testing of shells under uniform axial compression is the actual achievement of uniformity. It is extremely difficult to achieve in

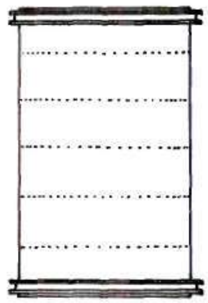
Table 2. Large Shell Details

Shell Number	Material	Diameter	Length	Skin Guage	Ring and Stringer Guage	Ring and Stringer Section
All Shells	2024-T3	72"	108"	0.025"	0.025"	"Z"

Shell Number	Stringer Spacing	Stringer Location	Ring Location
1	$\frac{3}{4}$"	Inside	Outside
2	1"	Inside	Outside
3	1"	Inside	Inside
4	$\frac{3}{4}$"	Inside	Outside
5	$\frac{3}{4}$"	Inside	Inside

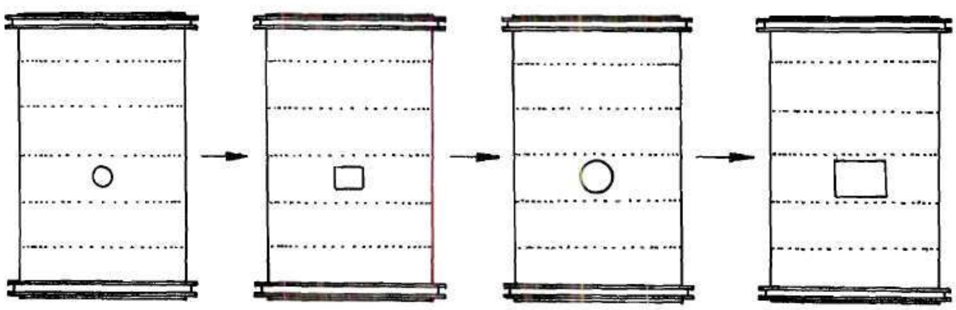
Table 3. Typical Test Series

1. Basic Shell Test

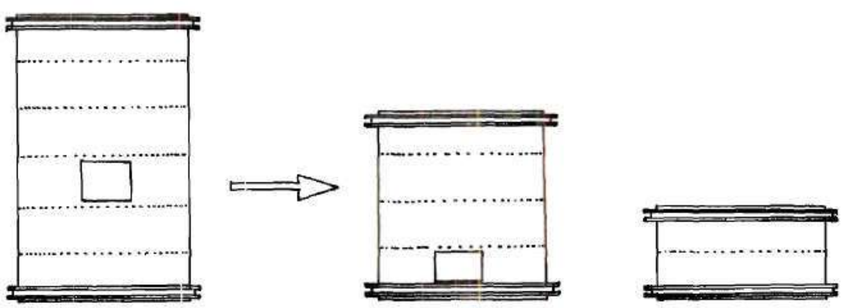


2. Stringer Modification

3. Cutouts (Both Round and Rectangular)



4. Alter Shell Length



both the shell ends and the loading devices those states of flatness and parallelism required for uniform load transfer to cccur. In addition, this difficulty increases greatly with increase in specimen size.

Small shells are normally loaded in a standard test machine, using heavy plates at the shell ends to transmit load. A typical arrangement of this type is shown in Figure 13. Since the plates required are not very large, they are not unreasonably expensive. Hence, they may be considered an integral part of a particular specimen system during a series of tests. This allows casting of the plastic model shell ends with epoxy while in place between the plates. The epoxy, which has characteristics very similar to plexiglass, flows into the gaps between the shell ends and the plates. Thus, intimate contact between the shell and plates is assured and good uniformity of loading is obtained.

Unfortunately, this technique is not applicable to the large shells. Loading plates of sufficient size for these specimens would be extremely expensive and most difficult to handle because of their great weight. In addition, no suitable grouting agent exists for use with these large vehicles.

Many past attempts to obtain a satisfactory load distribution in large shells have involved the use of an integrating structure near the shell ends. This has in most cases merely resulted in shifting the problem from the ends of the specimen to the ends of the integrating structure. As a result, those portions of the vehicles from which data could be obtained were considerably reduced. For this reason, the specimens used in the present program do not incorporate

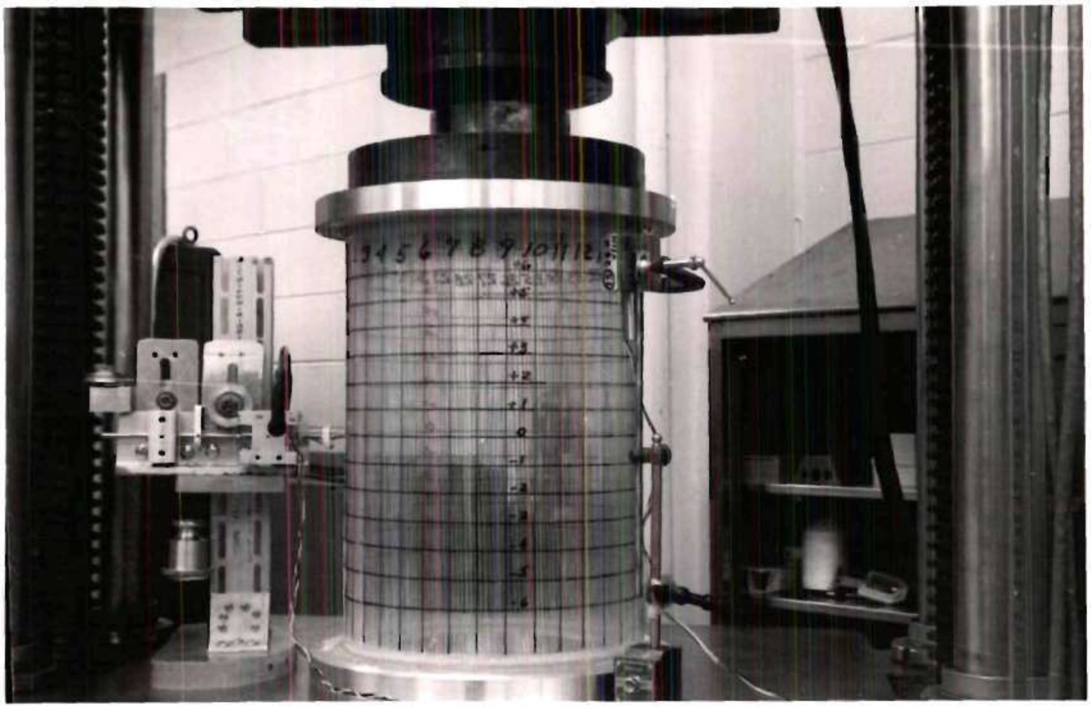


Figure 13. Typical Small Shell Loading Scheme

integrating structures; they are designed to be loaded directly on their ends.

The loading rig for the large shell tests was designed to aid the attainment of load uniformity without the use of integrating structures. The specimens are loaded by 72, 10,000 pound capacity hydraulic jacks equally spaced around the lower shell end (Figure 14). Eighteen ¼" thick ground steel plates are arranged in a circle between the jacks and the bottom of the shell. The load is reacted at the upper end by 18 pairs of one-inch diameter high-strength tie-rods which retain a circular I-beam in contact with the top of the shell. The rig is shown in Figure 15. The use of such a large number of jacks and tie-rods makes the system to a large degree self-compensating for non-uniformity.

In spite of this favorable rig design, tests showed that the ends of the first large shells were not suitably flat. The same was true of the loading ring in contact with the shell upper end, even though it had been commercially ground. Although the discrepancies in flatness were exceedingly small in comparison to the shell dimensions, they resulted in unsatisfactory load transfer to the shell. It was estimated that total out-of-flatness on the order of 0.001" to 0.002" would produce unacceptable strain distributions near the ends of the specimen ($> \pm 10\%$). Therefore, a method was needed to machine both the ring and the shell ends to tolerances well below these.

In order to accomplish this, a machining facility was set up, Figure 16. At the center of this was located a turntable mounted on a continuous tilt table bolted directly to the floor. Equally spaced

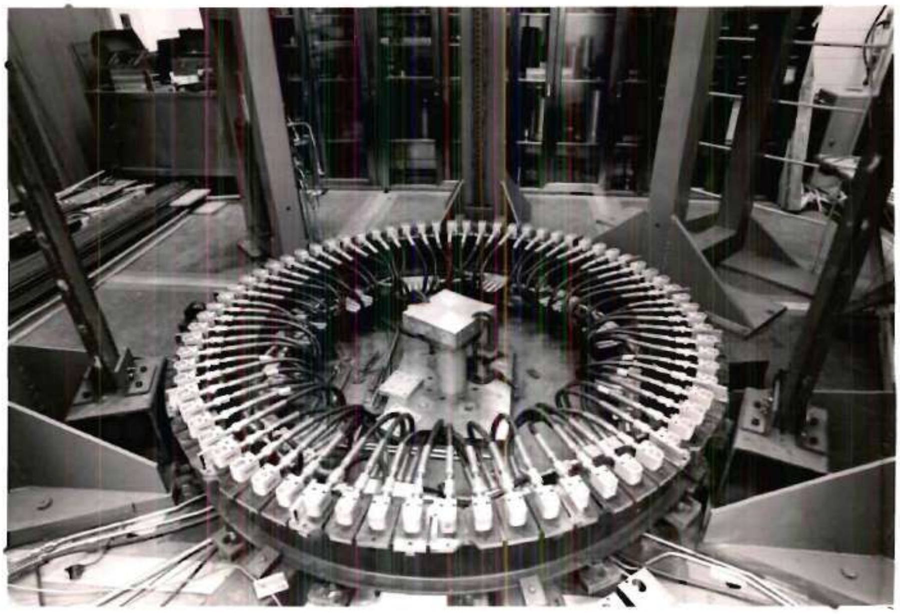


Figure 14. Jack Arrangement at Bottom
of Large Test Rig

Figure 15. View of Large Test Rig with Specimen in Place

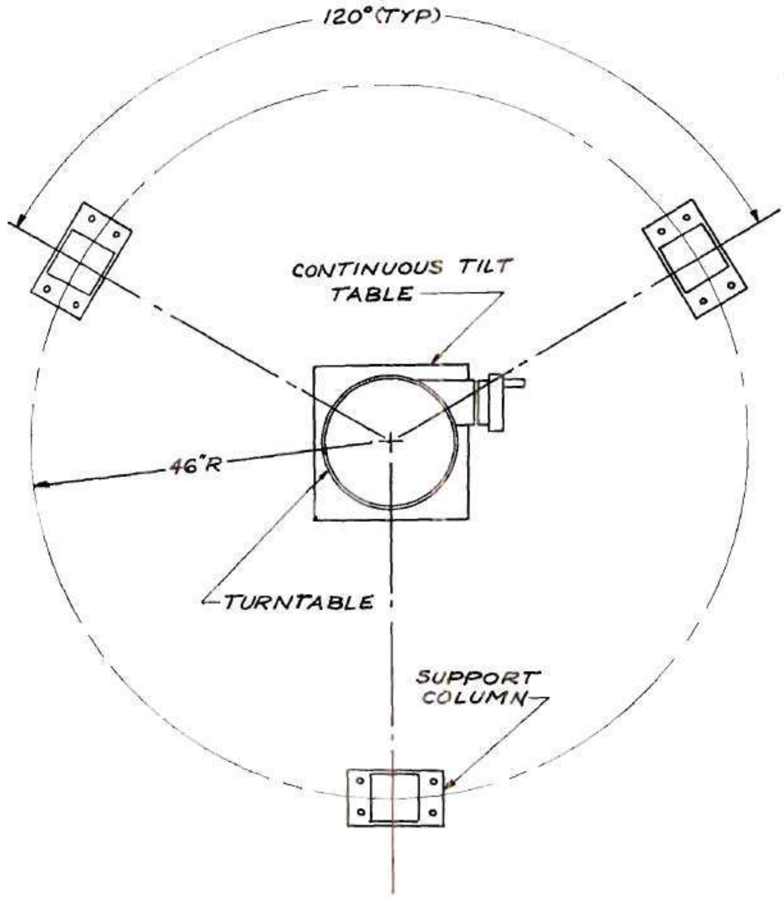


Figure 16. Plan View of Machining Facility

around the circumference of a 92" diameter circle were three 26½" tall columns made of 8" x 8" square hollow steel section ½" thick. These formed supports for the object being machined. On the turntable was mounted a transverse beam of the same square hollow steel section. At the end of this transverse beam was a screw adjustable X-Y table allowing precise movement in the vertical and radial directions. The drive motor for the particular machining operation in progress was mounted on this X-Y table (Figure 17).

The task of producing a flat loading ring was investigated first. Measurements were made of the commercially ground ring using a precision dial indicator mounted on the X-Y table of the rig described. Total variations from low to high spots on the ring surface of as much as 0.015" were recorded as the dial indicator was moved around the ring. These discrepancies were attributed to the nature of most commercial grinding operations. After forming, a ring of this type is usually slightly out of plane due to residual stresses produced in the forming process. Commercial grinding operations normally clamp the ring to a flat surface electromagnetically or mechanically. Hence, when the ring is clamped for grinding, its wave form is not the same as that in its free state and although the grinding operation results in a smooth surface, it does not necessarily enhance ring flatness. This problem can be overcome by very careful shimming of the ring before clamping, in conjunction with numerous light grinding passes on alternate sides.

The commercial grinding of a ring to the tolerances desired using this technique, however, is very expensive. Thus, it was decided

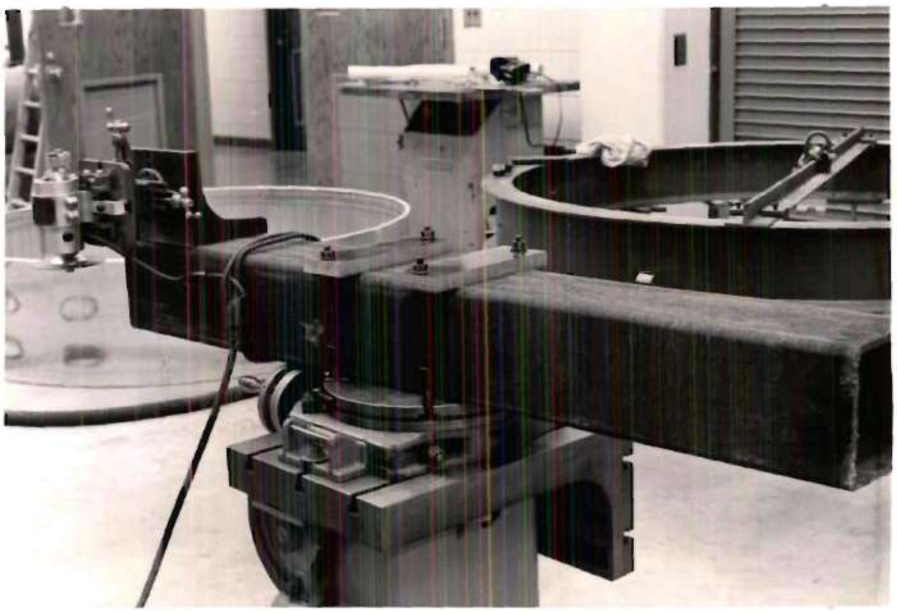


Figure 17. Arrangement of Turntable, Transverse Beam, and X-Y Table in Machining Facility

to grind the ring "in house" using generous portions of both engineering logic and tender care.

The design of the shell loading rig is such that it compensates for lack of flatness on the ring upper surface. Hence, only that side of the ring in contact with the shell need be "absolutely" flat. However, the idea of grinding only one face of the ring itself was discarded since this would result in uneven ring flange thickness and probably further ring distortion. Grinding of both ring faces was deemed undesirable because of the resulting appreciable reduction in ring section size and stiffness.

Therefore, 0.125" thick arc-shaped steel plates 1.5" wide were electrically plug-welded onto the lower ring face to form a raised section as shown in Figure 18. The plug welds were made alternately on opposite sides of the ring. Thus it was felt that the small amount of very localized heating would not appreciably deform the ring. The ring was then mounted on the supporting columns of the machining facility and shimmed until the upper surface was as nearly in a horizontal place as possible. In this manner, it was allowed to maintain its free wave form during the grinding operation. It was realized that this method of holding the ring was feasible only if very light grinding passes were to be used. The steel plates on the ring were then ground using a Skil 4", 4500 RPM, heavy duty grinder turning a 3" diameter ½" wide grinding wheel. To avoid deflecting the ring, a very small amount of material was removed on each pass of the grinder.

Subsequent measurement showed the newly ground ring surface to be flat to within $\pm$ 0.0005".

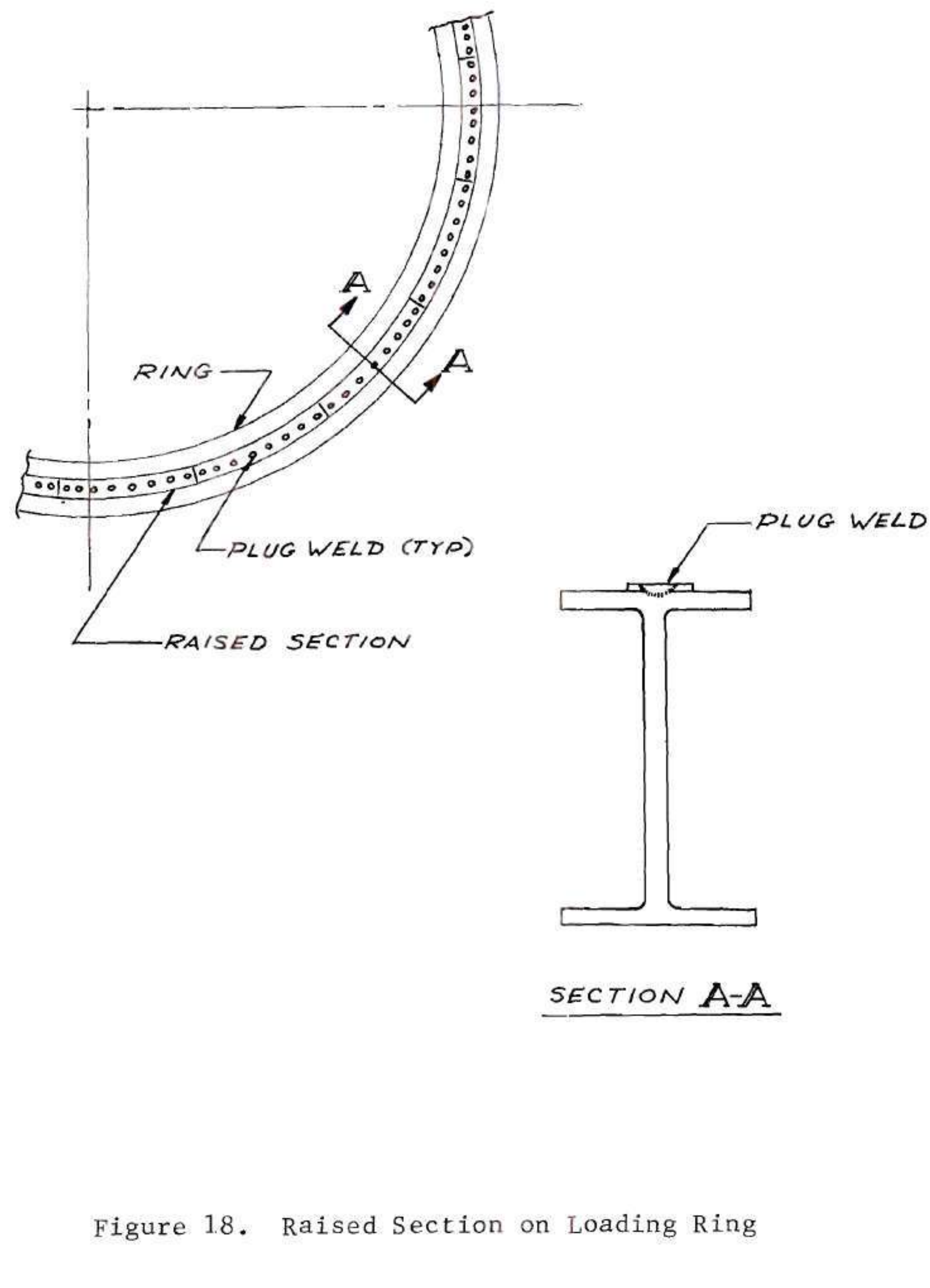


Figure 18. Raised Section on Loading Ring

Producing flat ends on the shells was the next task to receive attention. This was considerably more difficult than grinding the ring. The shells are rather unwieldy due to their size. In addition they are fragile. It was obvious that a great deal of care would be needed to assure the success of any machining operation.

To try out the concept of machining the shell ends on the facility constructed, two short shells were produced incorporating the same physical characteristics and construction techniques as the full-length specimens, Figure 19. One problem which readily became apparent was that of immobilizing the stringers during machining. It was obvious that a uniform flatness of the stringer ends could not be achieved if they were left to vibrate and chatter during the machining process. This problem was overcome by casting the stringer ends in place with a commercially available polyester putty commonly used as an automotive body filler. This material is inexpensive, easy to handle, fast curing, and readily machineable once cured. Typical appearance of the shell ends with stringers cast in putty is shown in Figure 20.

The short shells were then mounted on the facility previously described and the ends were machined using a high speed router motor (Stanley H39B) and a two fluted router cutter (Figures 21 and 22). The cutter was oriented horizontally. This was done for an important reason. With a vertically mounted cutter, it is impossible to completely remove axial float of the motor spindle. This axial movement, although very small, directly influences the quality of cut and the ensuing flatness of the work. With a horizontally mounted cutter, end

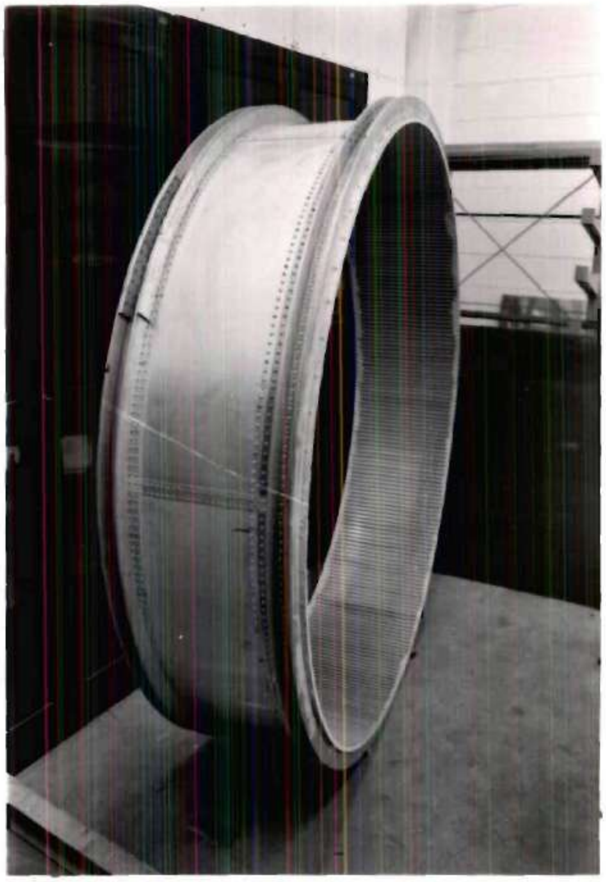


Figure 19. Short Shell

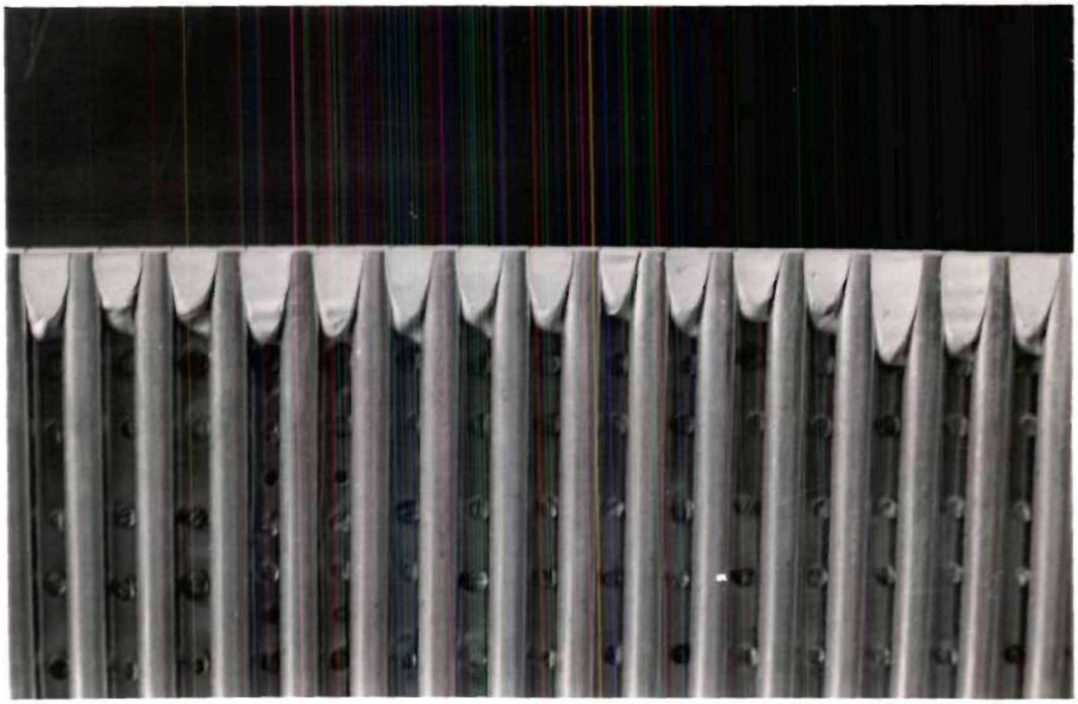


Figure 20. Stringers Immobilized in Putty

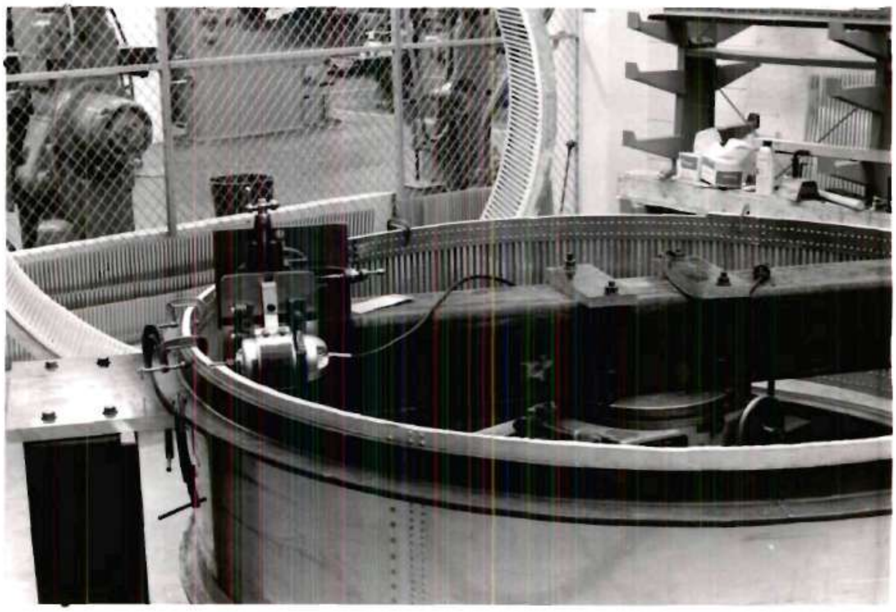


Figure 21. Router Mounting Details

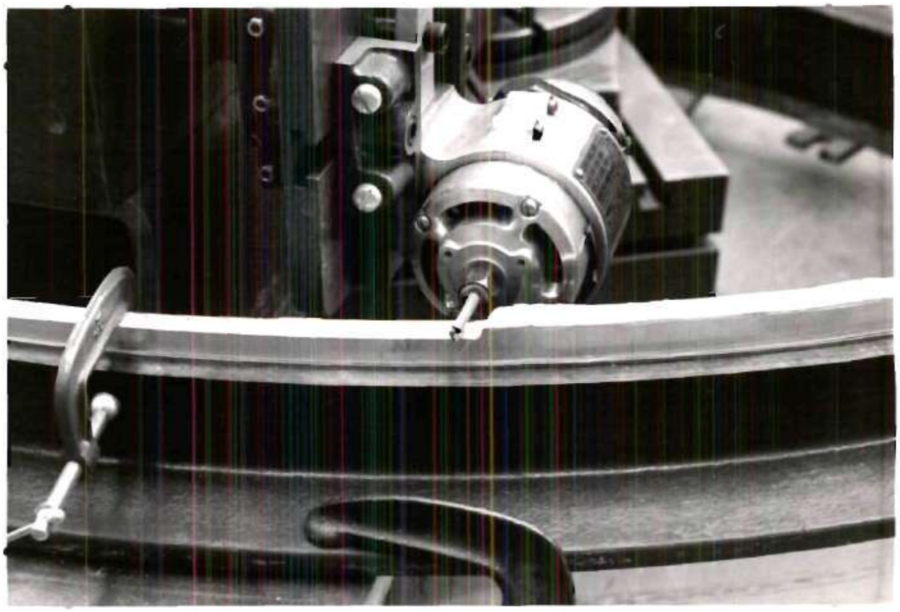


Figure 22. Close-up View of the Router During Initial Machining Pass on Shell End

float becomes a factor of no importance. Further, by using a very high tool speed, axial play in the motor bearings is compensated by gyroscopic forces. Hence, a very uniform cut is made possible, especially when a very small amount of material is removed on each pass. Flatness of the ensuing surface was further enhanced by use of the two fluted cutter which was moved at random speeds around the shell periphery. It can be shown statistically that a two-fluted cutter moved at random speed across the work is capable of producing the best possible surface. The resulting surface is shown in Figure 23.

Measurement of the newly machined shell ends showed them to be flat within $\pm$ 0.0005".

After the loading ring and shell ends were machined flat, one major obstacle to the attainment of uniform load distribution remained: that of obtaining equal tension in the 36 tie rods. The load reacted by each pair of tie rods is measured by specially designed load cells. These showed the load distributions in early tests to be unsatisfactory. It was subsequently attempted to adjust the tie rod tension by precise torqueing of the nuts at the tie rod ends. This did not produce the desired result. Consequently, a hydraulic jack was placed between the top of the loading ring and the plate joining the inner and outer tie rods at each of the 18 tie rod stations. The jacks were connected by a manifold and thus compensated for discrepancies in tie-rod adjustment. The arrangement is shown in Figure 24.

That the described procedures solved the problem of obtaining a uniform load distribution in the shell can readily be seen from the subsequently obtained data shown in Figures 25, 26, 27, and 28.

Figure 23. Resulting Surface After Machining

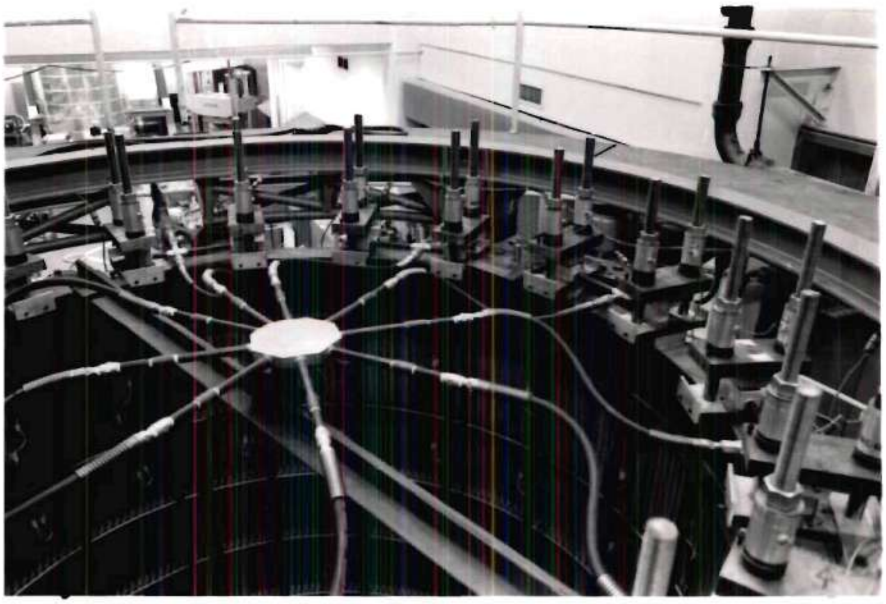


Figure 24. Jack Installation at Top of Shell

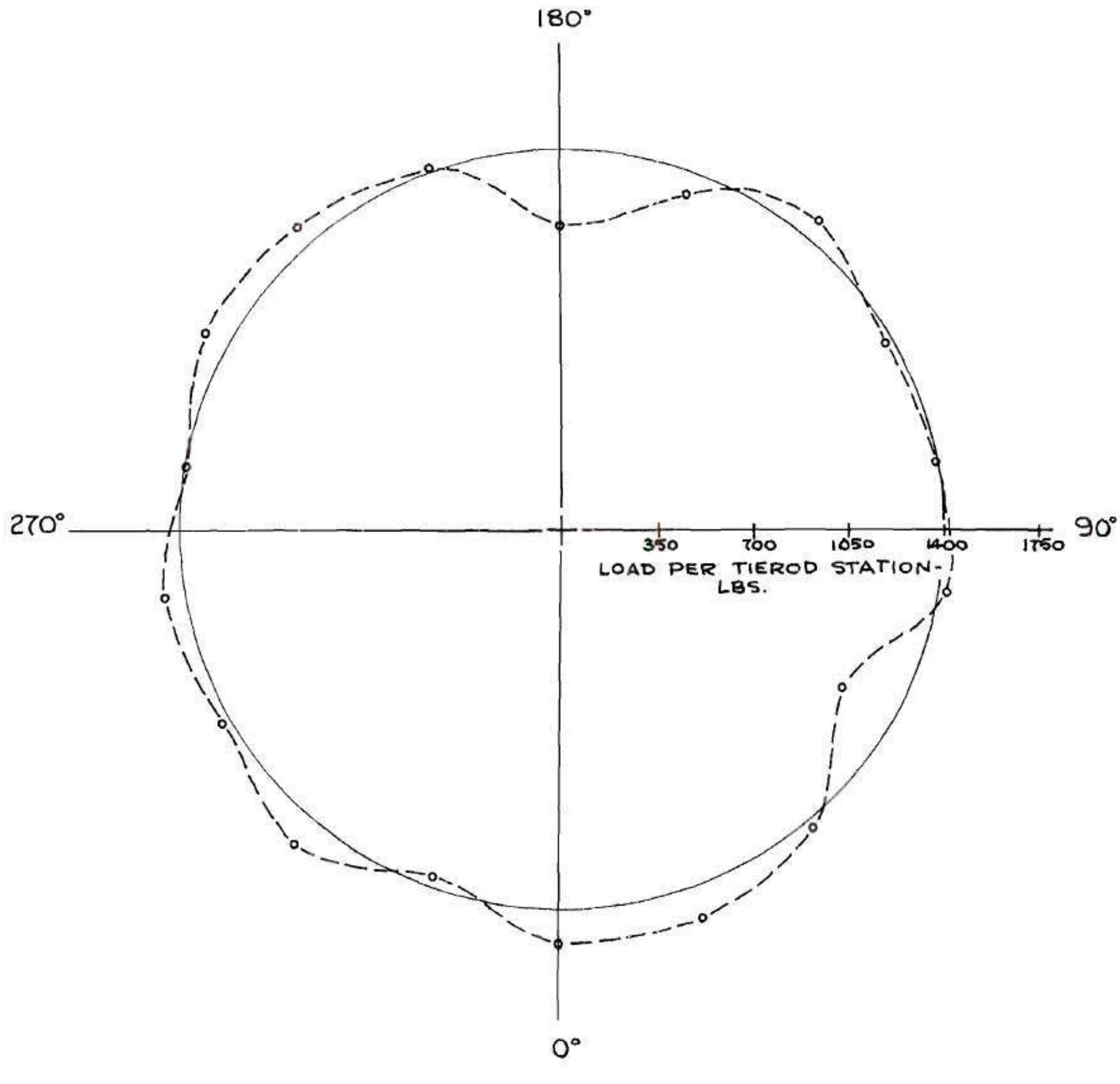


Figure 25. Load Distribution on Large Shell

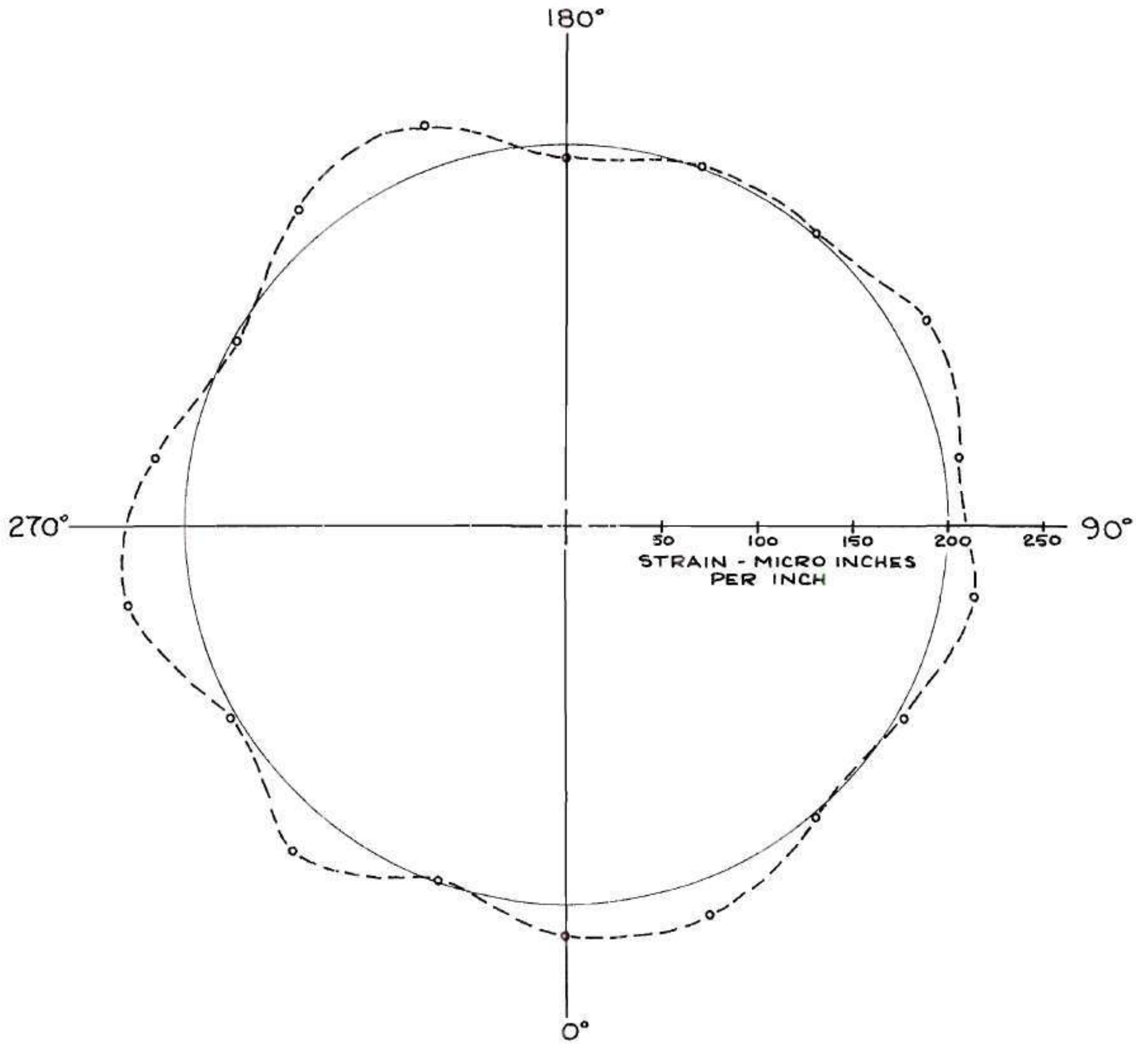


Figure 26. Strain Distribution at Top of Large Shell

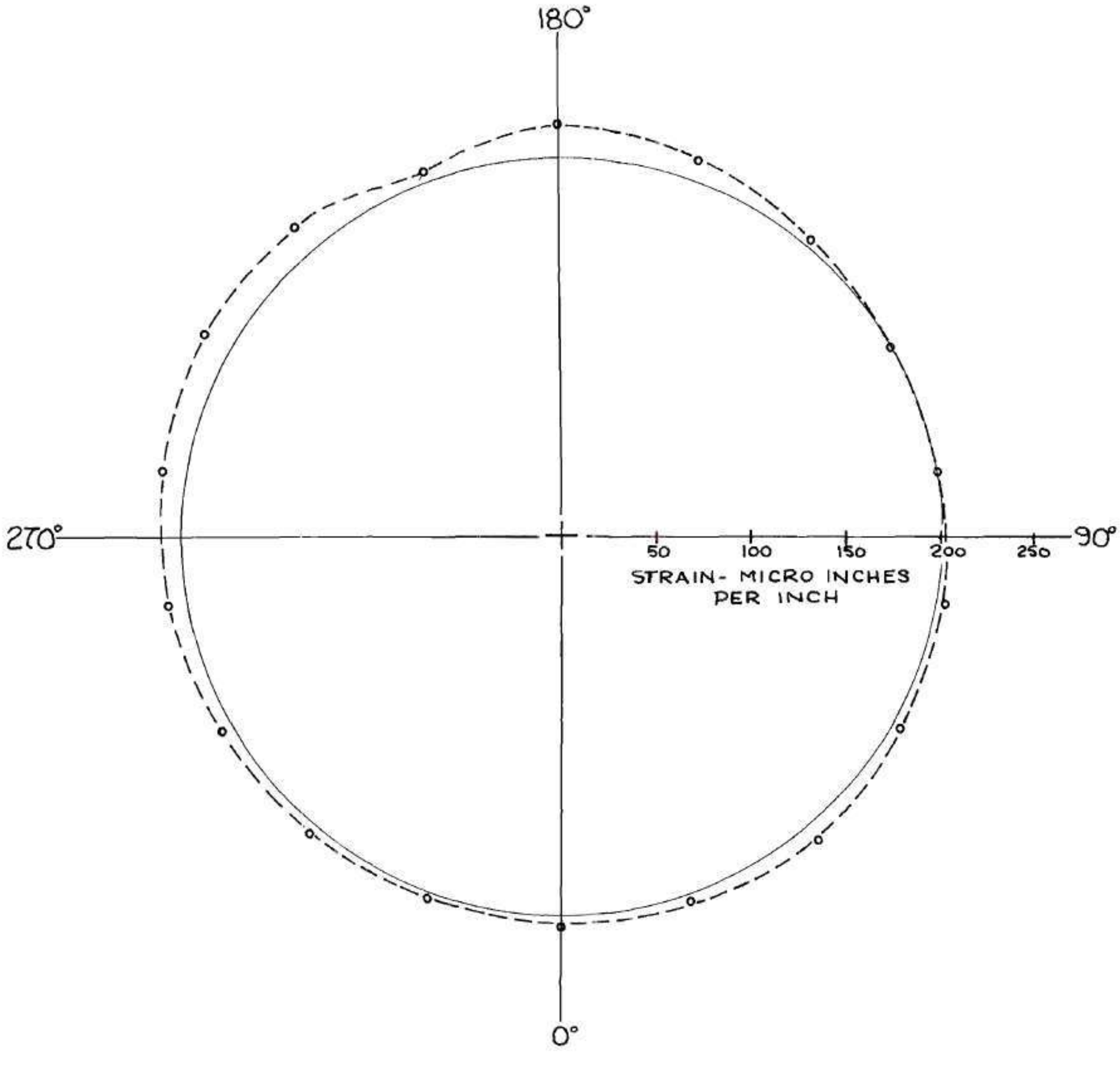


Figure 27. Strain Distribution at Middle of Large Shell

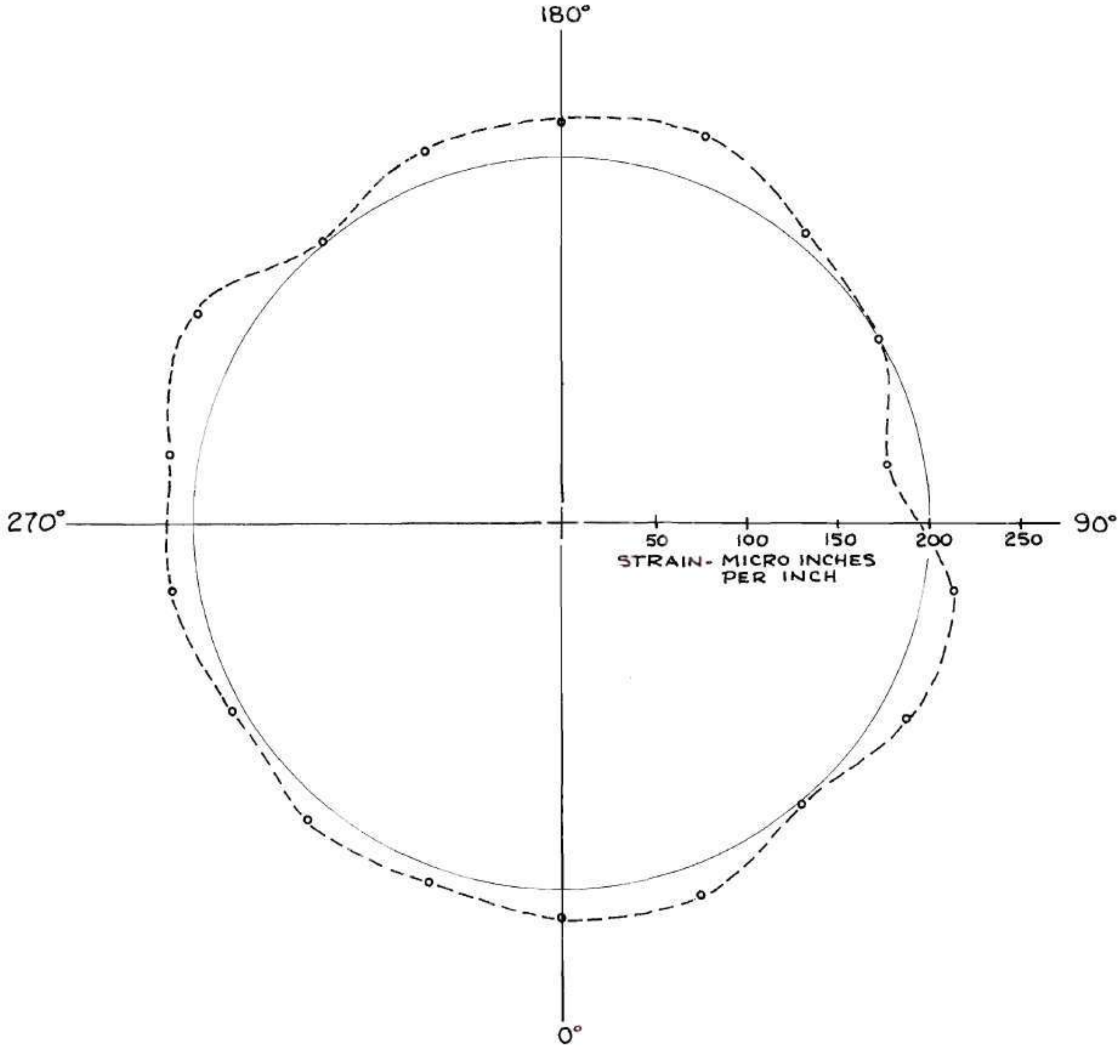


Figure 28. Strain Distribution at Bottom of Large Shell

Stringer Modification

Ability to modify the stringers with a shell in place on the test rig was considered the next desirable technique to develop. It was envisioned that this modification process would occur in several steps: the first removing the reflex from the stringer upper flange and each succeeding one removing more of this flange (Figure 29).

In designing a tool to accomplish this task, it was necessary to consider several factors:

(1) The stringers are thin and flexible.

(2) They are bonded to the shell wall; the bonding could be damaged by excess impact or force normal to the shell wall.

(3) The resulting cut should be of high quality and closely aligned with the stringer axes.

(4) It should be possible to closely control the amount of flange material removed.

The first two factors influenced the choice of cutter. The need to avoid impact loading and excessive normal force made a toothed or fluted rotating cutter undesirable. The use of a plunging cutter such as a sabersaw was discarded for the same reasons. Abrasive cutting wheels, however, appeared to present none of these drawbacks for the present application. The wheels provide a very positive, smooth, cutting action. Therefore, a Pekay 6" DIA abrasive composite wheel (#1902-46-HSS) rated for 12,500 R.P.M. was selected as appropriate for the proposed task.

An Ingersoll-Rand (#A98253) air-turbine motor capable of turning

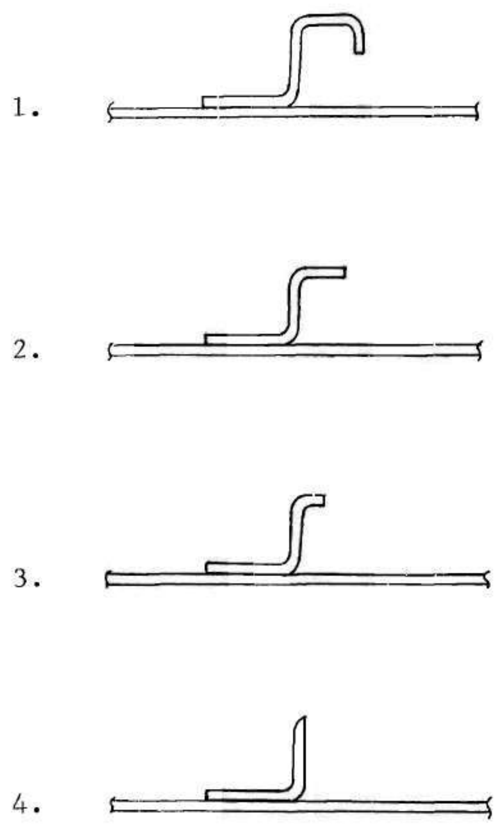


Figure 29. Stringer Modification Steps

at 12,500 RPM was chosen as the source of power. The advantages of an air motor of this type are light weight, compactness, good power, high torque at low speeds, and continuously variable speeds.

In order to reduce the time required for the modification process, the tool (Figures 30, 31, and 32) was designed to cut three stringers at a time. Three abrasive wheels are driven off the air motor by a flat belt.

Alignment of the cuts with the stringer axes is accomplished through four flanged wheels on the tool. These roll on the stringers and provide accurate guidance as the tool is moved (Figure 33). The legs on which the wheels are mounted are spring loaded. Hence, initial contact of the tool with the shell is made as the wheels touch the stringers. When this occurs, the cutting wheels are well clear of the stringer flange. As the tool is further depressed, cutting begins. Adjustable stops on the legs control the depth of cut and hence protect the shell wall. Lateral movement of the cutting wheels for subsequent cuts is provided by an adjustment of the tool spindle.

Stringers on sample panels were cut very easily with this tool. No noticeable vibration of the stringers was observed and the quality of the cut edges was good.

Machining Cutouts

Unlike the small plastic models, which can be provided with cutouts using standard shop equipment, the larger shells pose unique problems in this respect. Machining of the shell ends, discussed earlier, had been aided by the presence of end reinforcement rings and the fact

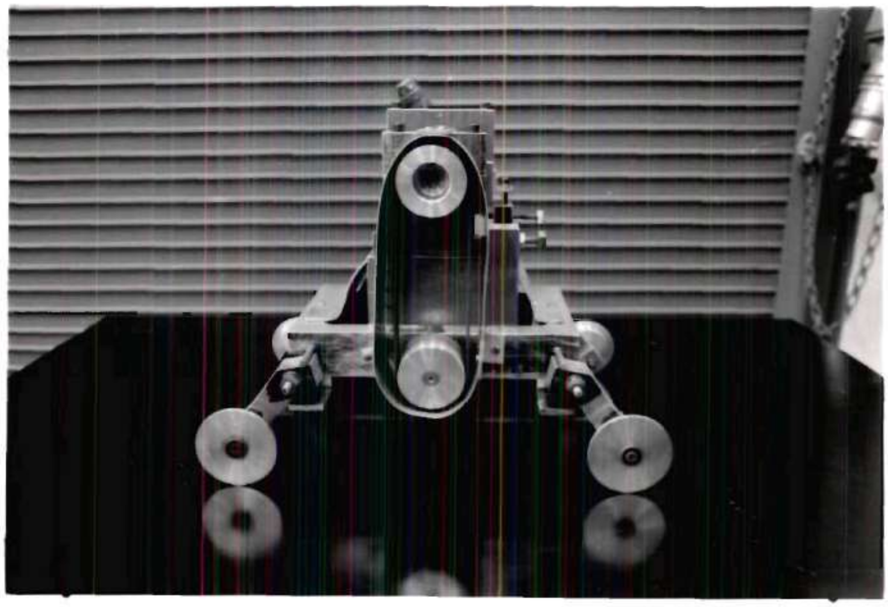


Figure 30. Stringer Cutting Tool--

Side View

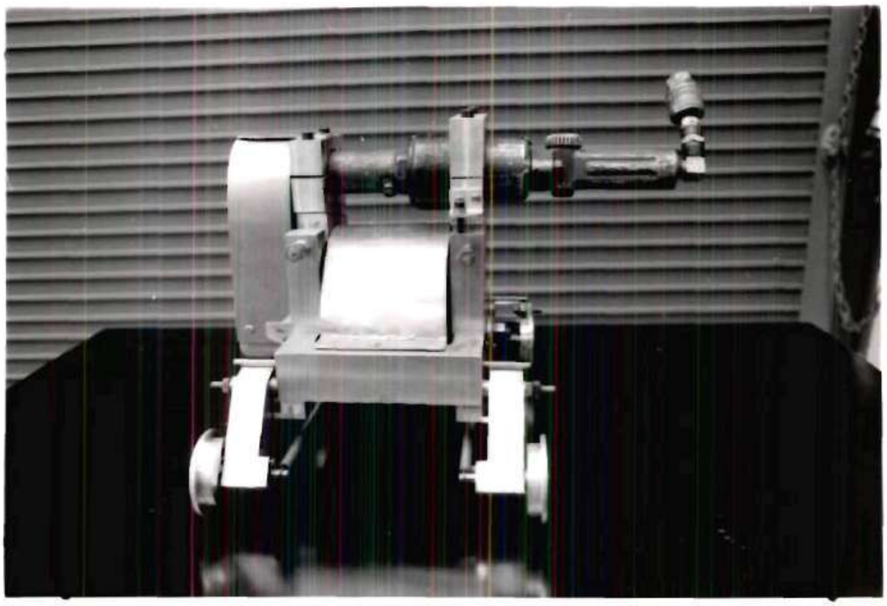


Figure 31. Stringer Cutting Tool--

End View

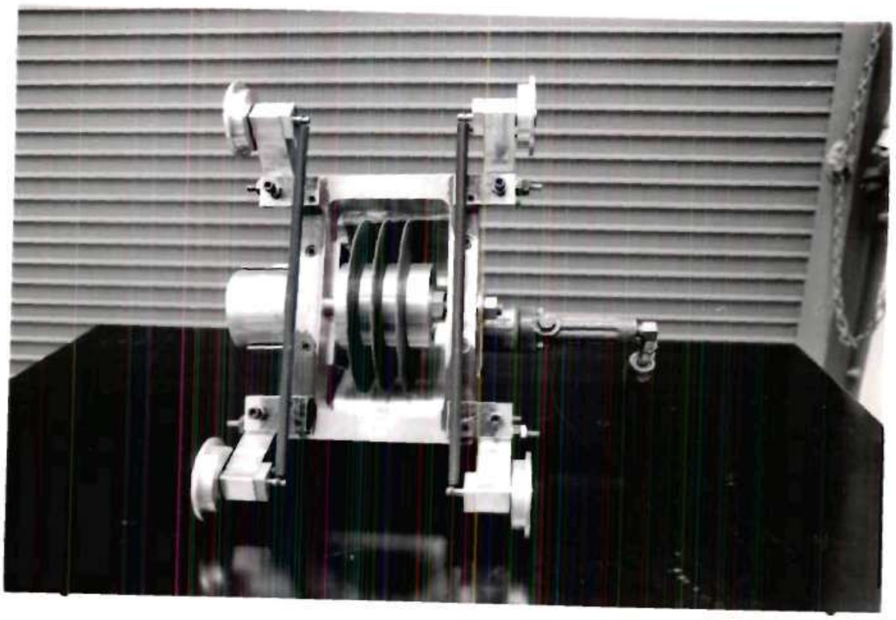


Figure 32. Stringer Cutting Tool--
Bottom View

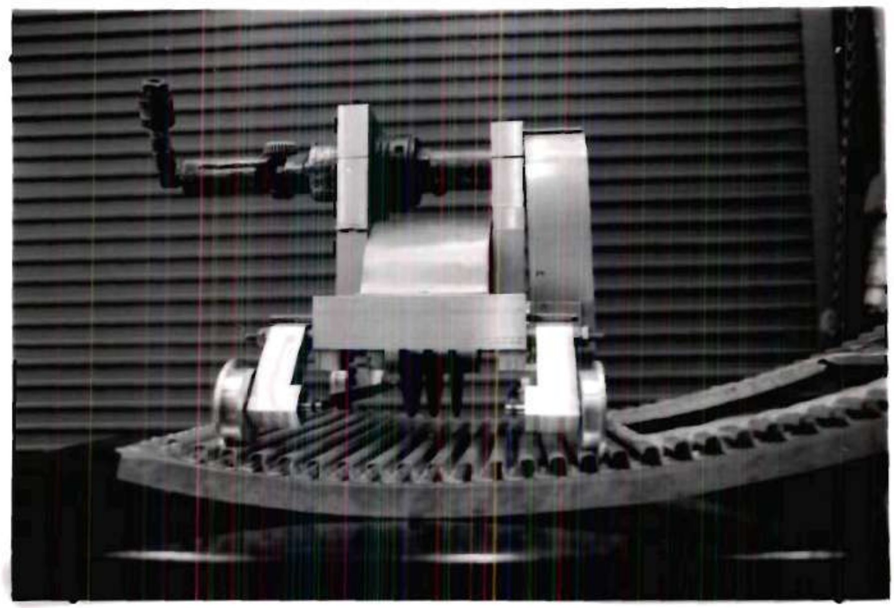


Figure 33. Stringer Cutting Tool on Panel

that the stringers are riveted near the ends. In machining a cutout at the middle of the shell, however, one would be dealing with rather delicate 0.025" thick skin and bonded stringers of the same guage. Since various cutout shapes were desired, the cut would in some cases be discontinuous due to the shell curvature. It was also desired that this process be carried out with the shell in place on the test rig.

The use of a sawing-action tool was quickly discarded for the machining task because of the excessive vibration and loading that such devices tend to apply to the work. A cutting technique was sought which would allow very precise control over the amount of material removed, preferably in a multiple pass operation. In this way it was felt that vibration, and deflection of the shell wall and stringers, could be kept to a minimum.

Because of the excellent characteristics it displayed when powering the stringer cutting tool described earlier, the Ingersoll-Rand air motor was again chosen as the source of power. It was equipped with a high-quality 3/8" capacity chuck. This was used to hold a 3/8" diameter four fluted milling end cutter.

It was felt that machining cutouts on the shell in place on the test rig could be most conveniently done from the outside of the shell. However, it was not known which direction of cut, from the outside in or from the inside out, would pose the fewest problems and give the best cut. Hence it was decided to try both, at the same time gaining practical experience and testing the proposed cutting process.

A representative panel was therefore constructed (Figure 34). Since machining of a square hole from the "inside" of the panel could

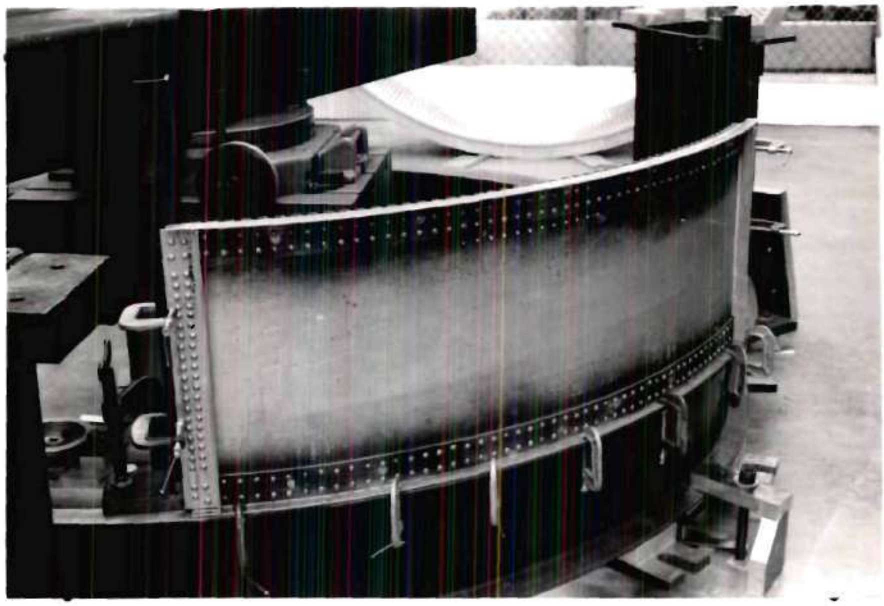


Figure 34. Test Panel for Machining Cutouts

be accomplished with very little modification of the existing machining facility described earlier, it was accomplished first. The air motor was mounted on the X-Y table which allowed precise control of cut depth and vertical cutter travel. Tool motion in the circumferential direction was provided by the turntable. The stringers were stabilized by a cast ring around the area of the planned cut using polyester putty (Figure 35). Very light (approximately 0.005") cuts were made on each successive pass and a very slow rate of feed was used. The cutter was turned at approximately 4 - 5,000 R.P.M. The quality of cut on each successive pass was excellent (Figure 36). No undue vibration was noticed. The stringer bond was seen to be intact when that depth of cut was reached. The skin was penetrated using several light passes. The ensuing cutout edges were extremely smooth (Figure 37). No stringer delamination was evident upon close visual inspection.

The machining facility was next modified to allow the production of a circular cutout from the "outside". The continuous tilt table was adjusted so that its upper surface was vertical. The turntable was then mounted off-center on this surface. The X-Y table supporting the air motor was then bolted directly to the turntable to give the desired diameter of cutout. The arrangement is shown in Figure 38.

The stringers around the projected cutter path were again immobilized in polyester putty. The machining operation was conducted as before, using a very slow feed speed to make extremely light cuts. Figures 39 and 40 show the process. Cutting a hole from the outside proved no more difficult than from the inside using this procedure.

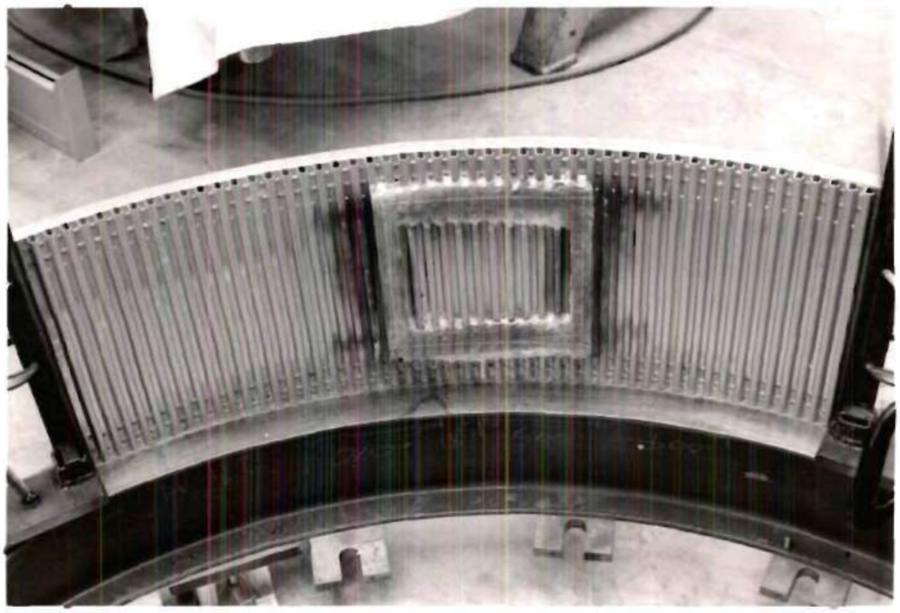


Figure 35. Stringers Cast in Putty Before Machining

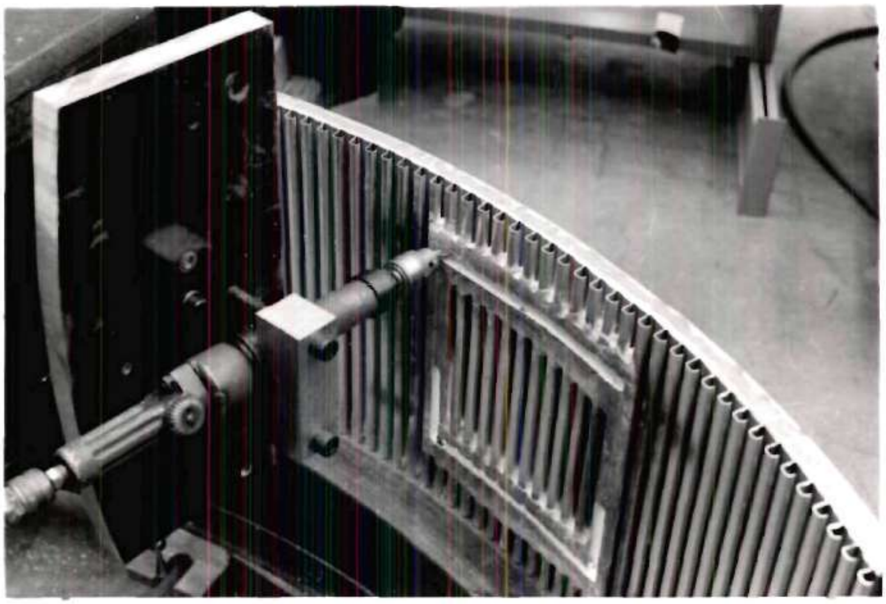


Figure 36. The Machining Operation

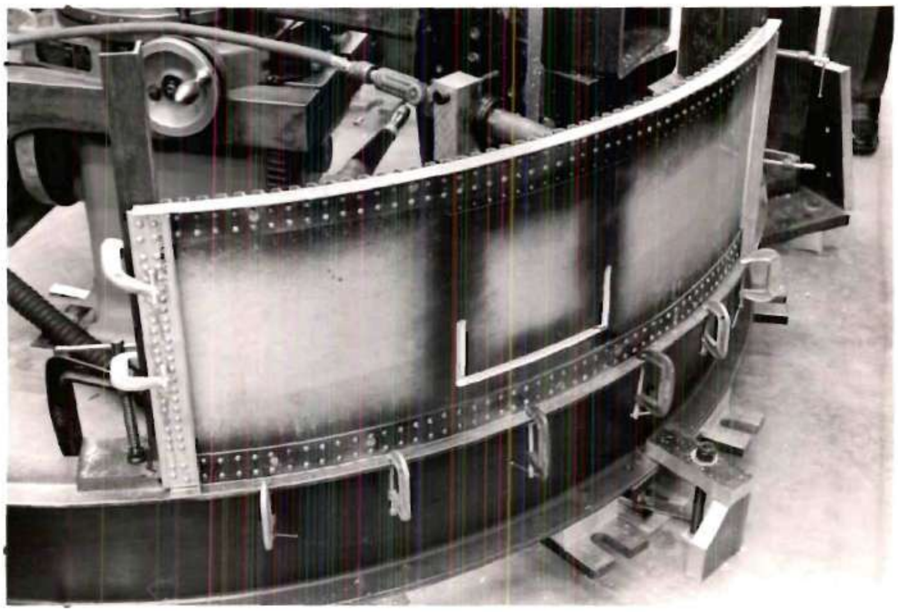


Figure 37. View of Cut in Progress Showing Smooth Edges

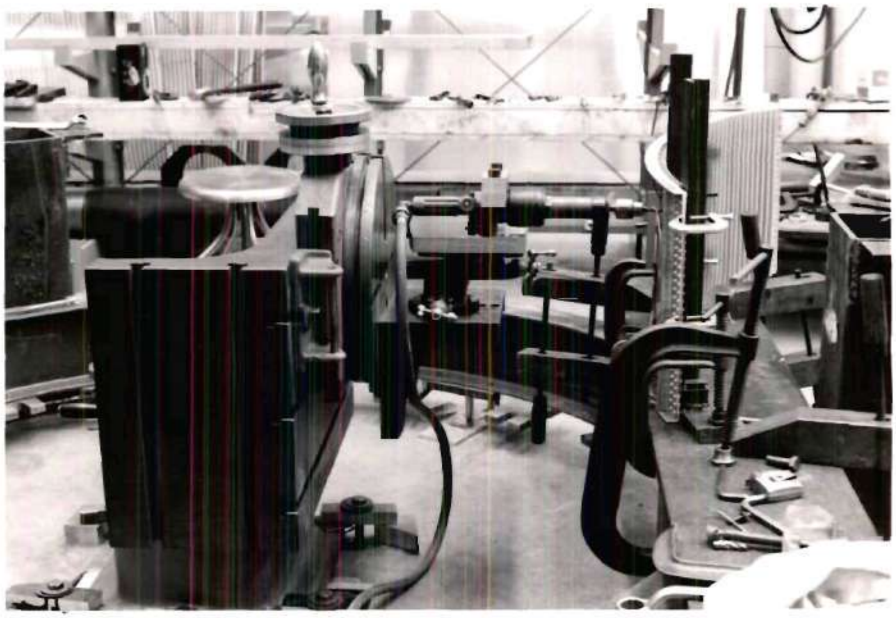


Figure 38. Facility Arrangement for Machining Round Hole

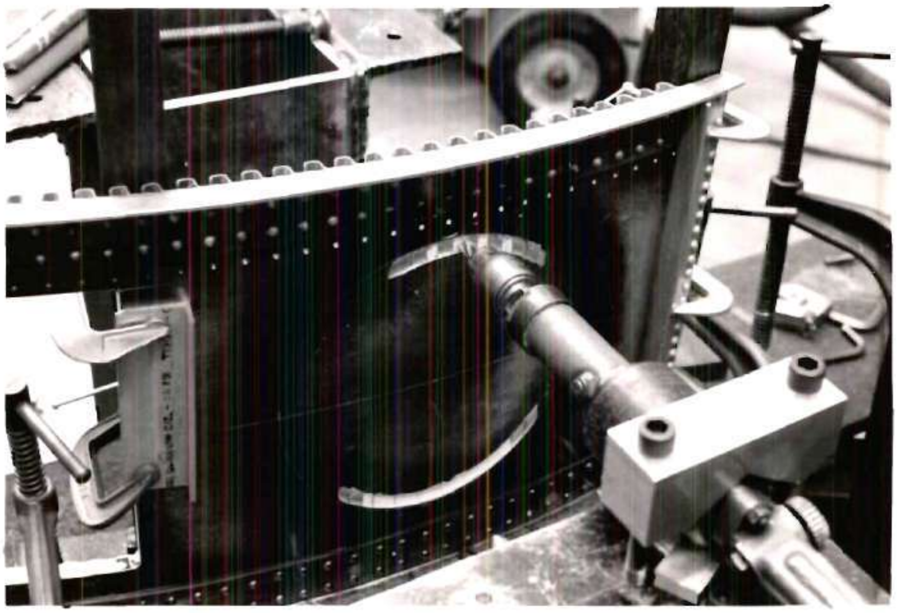


Figure 39. Machining of Round Hole in Progress

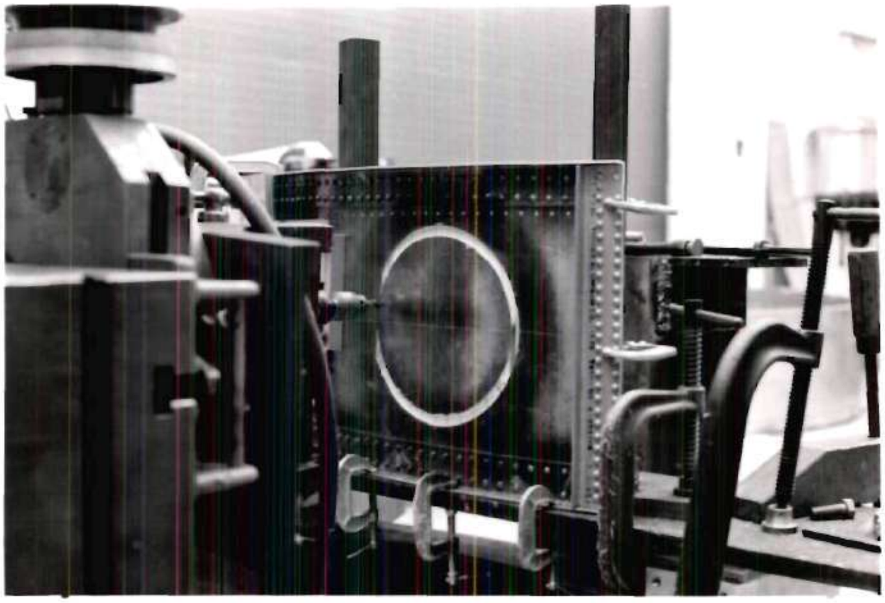


Figure 40. Machining of Round Hole in Progress

Again, the quality of the cutout surface was very good and no stringer delamination was evident.

The two completed cutouts are shown in Figure 41. Using the procedure described it will be possible to machine such cutouts in the large shells without undue difficulty either from the inside or outside.

Altering Shell Length

The last step in the planned shell modification program for which it was necessary to develop suitable capability was that of cutting a shell into parts, hence producing two or more shorter specimens. It was desired that the cutting process used produce a square cut of high quality without damaging either of the ensuing shell segments.

A step-by-step procedure was developed by which this sectioning process could best be carried out. Starting with the basic shell, new end reinforcement rings would be carefully riveted onto it in suitable proximity to the desired cut. Precisely machined blocks would be located between these rings at regular intervals around the shell circumference. These would support the two ensuing shell segments during and after the cutting process. After completion of the cut, the segments could then be carefully separated and the newly cut ends machined using the procedure detailed earlier in this work. Table 4 outlines the process.

In order to prove the merits of this scheme in practice and to discover unforeseen problem areas, it was decided to section a test panel. A panel was made (Figure 42) using the same material and construction as those of the large shells. Two curved angles formed by

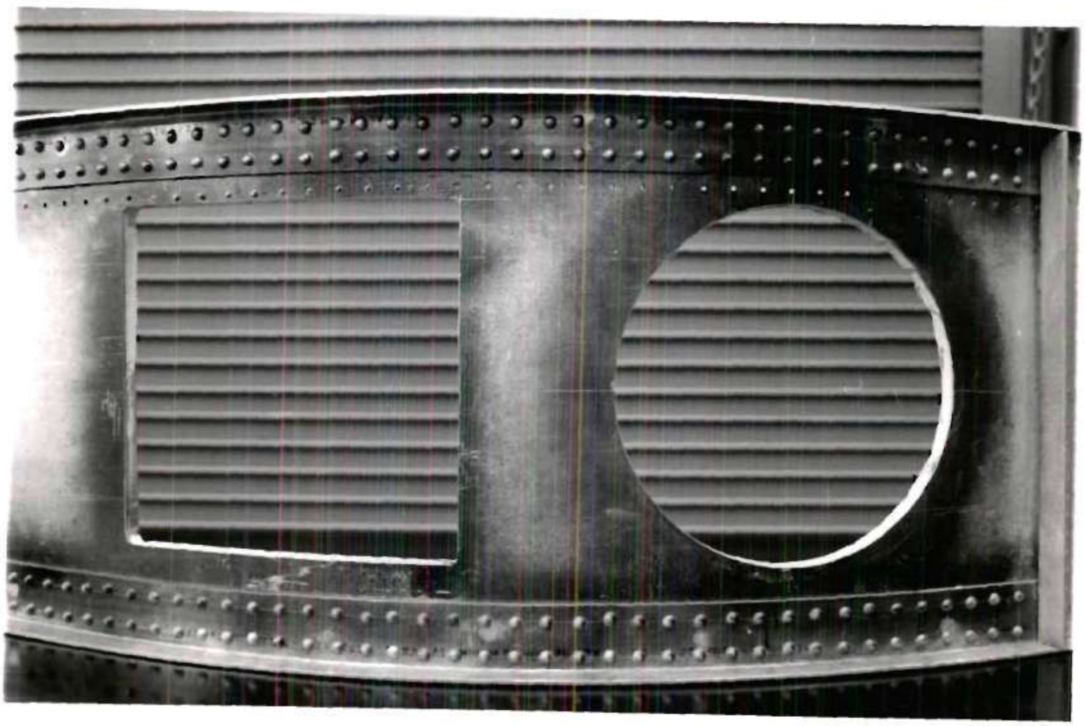
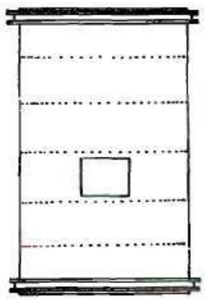


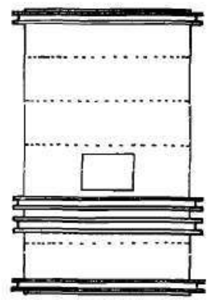
Figure 41. Completed Cutouts

Table 4. Proposed Shell Sectioning Process

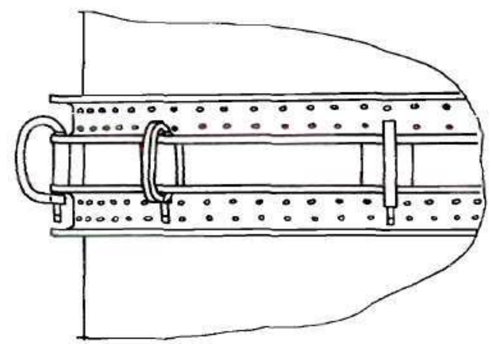
1. Basic Shell



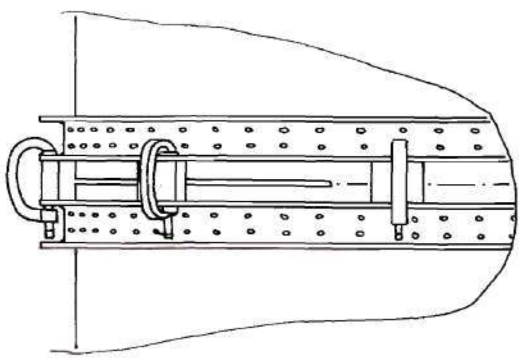
2. Attach Rings



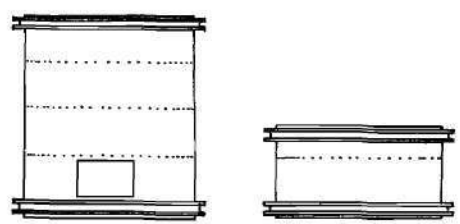
3. Install Spacers



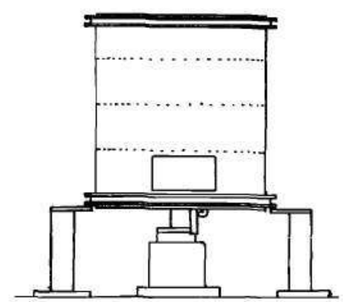
4. Cut



5. Separate



6. Machine Ends



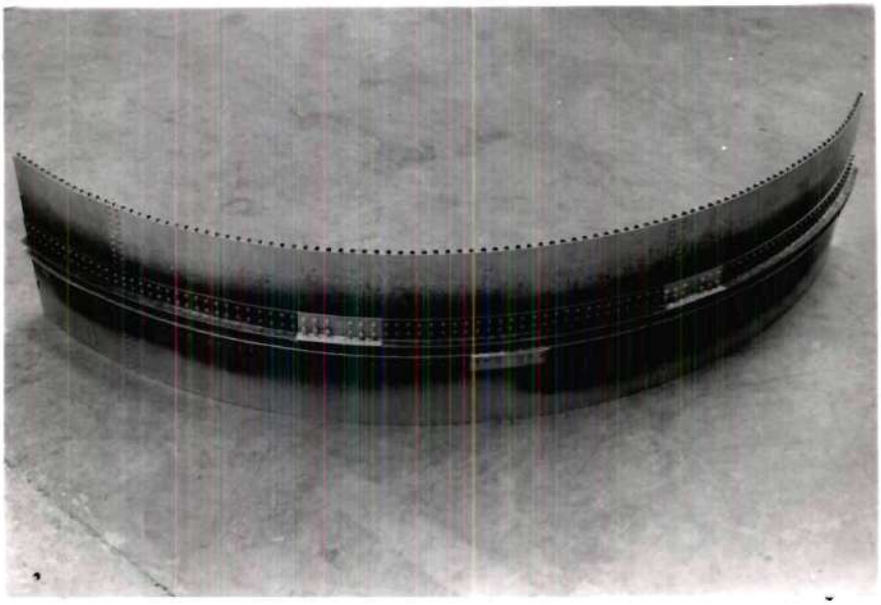


Figure 42. Test Panel for Sectioning Process

hammering were riveted to the panel to provide reinforcement on either side of the cut.

The panel was then cut using the machining facility described previously. Power was supplied by the same Ingersoll-Rand air motor used before, driving a 6" DIA composite abrasive wheel as the cutting agent. The motor was mounted vertically on the X-Y table and the abrasive wheel turned in a horizontal plane.

Using the scheme outlined and the set-up described above, the panel was cut very easily. There was no evidence of excessive vibration. The ensuing cut was smooth and square (Figure 43). Close visual examination of the stringers showed no signs of delamination or deformation.

The machining facility can easily be modified to section a full-size shell. All that is required is a taller column under the turntable.

Inspection of Stringer-to-Skin Bond After Machining

After completion of each of the previous machining tasks, the stringers were closely examined visually for delamination with negative results. This is admittedly a crude test and in the future it may be desireable to employ a non-destructive test method to more accurately examine the local bonded areas after machining operations of this type have been performed. One technique which shows promise in this regard is the use of a heat flow comparator (6). Ultrasonic bond testing techniques might also prove useful; however, they have not been refined to allow their practical use of such small bond areas.

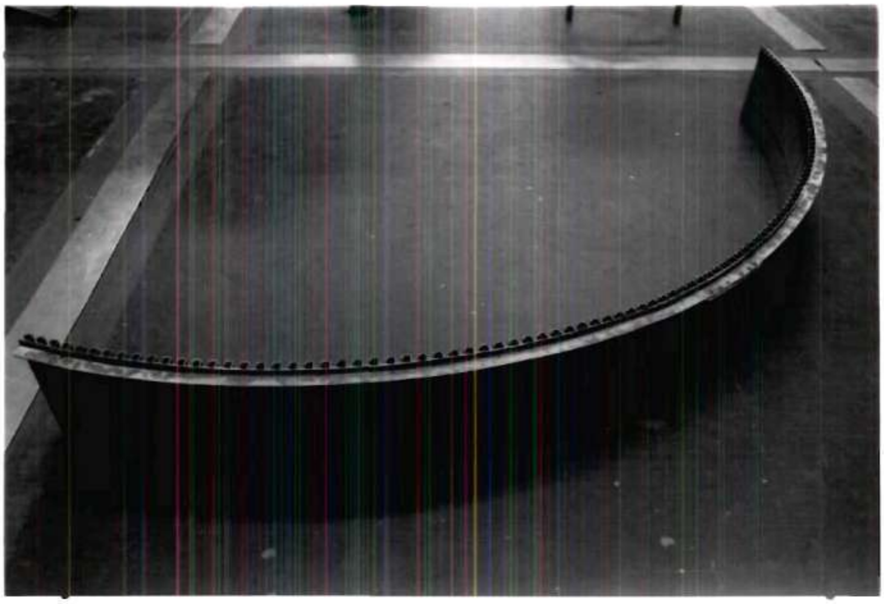


Figure 43. Panel After Sectioning

CHAPTER IV

CONCLUSIONS

The prime engineering problems which exist in the fabrication of versatile plexiglass model shells and in tests on large scale metal shells have been resolved by the work carried out in this study.

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